DESIGN OF A SUBMERSIBLE VEHICLE

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CERTIFICATE

This is to certify that this work on "Design of a Submersible Vehicle" by Parande Rajendra Shivaji, has been carried out under my supervision and has not been submitted elsewhere for the award of a degree.

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DEDICATED TO MY FATHER

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ABSTRACT

A design of a remotely controlled, unmanned submersible vehicle for inspection of nuclear spent fuel storage tanks is proposed. The submersible vehicle will be used for radiation detection and inspection of the spent fuel rods.

The designed submersibles is one of the first vehicles developed,specifically for applications in a nuclear power plant. It will be one of the smallest submersibles available, amongst the existing, unmanned self propelled submersibles.

The submersible has a closed framework metal structure, eliminating the need for underwater equipment. It is propelled with three screw propellers, providing two translational motions and one rotational motion. A C.C.D camera for observation and inspection is mounted on a pan and tilt mechanism providing additional degree of freedoms for observation. The power and signal transmission to the vehicle is through an umbilical cable. The magnetic compass and the depth sensors assist the operator to navigate the submersible.A radiation detector will give the radioactivity level in the tank.

Though the vehicle is designed for a nuclear power plant it will also find applications in hydroelectric and thermal power plants and in oil and gas industry, for inspection at shallow depths.

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INTRODUCTION

1.1 Introduction to Submersibles

1.1.1 Definition

A submersible is defined[20] as a vessel capable of operating underwater ,while a submarine is a ship capable of operating submerged . The relationship of a submarine to a submersible is that of a ship to a boat.

1.1.2 History

The history of man's ability to develop means for directly exploring ,scientifically studying and finally exploiting the bottom of the ocean and other underwater environments falls into four eras.[20]

The first era ,wherein he can go beneath the water surface and to shallow depths by himself ,starts as far back as 4500 B.C.,when mother of pearl was used to decorate the Vase of Mesopotamia. The second era can be divided into two phases:phase-1 in which he encapsulates himself into a rather crude vehicle and is again limited by depth ,endurance ,range , and speed;phase-2

where a more sophisticated version known as the submarine became available. Edward Halley, who discovered the comet named after him is the first person to be credited with the building of the first practical diving bell. This was in the middle of the 17^{th} century. The first reported use of a submarine for military purposes is credited to Bushnell who in 1776 built one called 'Turtle'.

Era three is the one wherein man has designed and used, generally for constructive purposes , much smaller vehicle called the submersible .The first submersible was developed by Beebe in 1930 .In 1960 Piccard and Walsh dove to the bottom of the challenger deep (1200 m) in the submersible called 'Trieste'. The fourth era may be defined as the period in which a highly specialised effort to study and harvest the resources of the oceans has been successfully consummated using an unmanned submersible . U.S. Navy's CURV-1 (Cable-Controlled Underwater Vehicle) was one of the first unmanned vehicles. A number of vehicles were built after the 1970's. Most of these vehicles were used for ocean exploration. In 1974 eight of these were built,by the end of 1980 the number of these vehicles had increased to 31, mainly due to the growth of the oil and gas industries.

1.1.3 Classification

Submersibles can be classified as manned or unmanned depending on the presence or absence of a human operator, in the vehicle.

As the name suggests the manned submersible permits placing of the human eye ,hand and the brain directly at the point of

observation. The unmanned submersible refers to relatively small self propelled vehicles. It is also called as the remotely controlled vehicle, or remotely manned underwater vehicle. The title emphasizes the fact that a human being is not inside the vehicle. Instead of being at the view port he is on the surface observing a TV monitor.

The unmanned submersible can be further classified as teleoperated, wherein the control is in the hands of the operator and autonomous in which the vehicle can operate on its own without operator interface.

Based on the signal and power transmission system the submersible can be classified as tethered or untethered. In case of tethered submersibles the power and signal transmission is through a cable permanently connected between the vehicle and the surface support. In case of untethered vehicles, signal transmission is through radio communication, acoustics or optical sensors.[13]

1.1.4 Manned Submersibles vs Unmanned Submersibles

The advantages of unmanned submersibles over manned submersibles[20,45] can be listed as follows :

a] Small in size and low weight.

b] Enables operation in hazardous area without endangering personnel.

c] Unlimited operational endurance on the working site because of cable link to the surface.

d] Ease of changing crews without disrupting the mission.

The negative features of unmanned submersibles in relation to the manned submersibles are as under :

a] The umbilical cord (cable) causes difficulties in maneuvering,[15] even to the most experienced pilots due to the possibilities of cable entanglement with the vehicle which is generally open space framework type,or with objects on work site.This limits the use of this vehicle to specific applications.

b] Many manipulative and observational tasks require 3D viewing to be effective. Most sophisticated equipment and techniques cannot be a substitute for the human eye. The ability to react, to pursue the unexpected, to alter plans quickly and continuously in response to a changing situation is the most durable virtue of manned submersibles.

c] Possible extensive loss to property if power should be lost and the vehicle surfaces out of control, since it is operated with a slight positive buoyancy, maintaining submerged positions using vertical thrusters.

d] The intense concentration required by the operator to guide and control the vehicle limits the optimum time of the operator to about 3-4 hr. This necessitates staffing of more than one skilled and experienced operators to work on shifts.

1.1.5 Submersible Characteristics

On the basis of the existing unmanned submersibles,[7,12,23] certain common features regarding them can be observed. The following discussion will give the general characteristics of the unmanned submersibles. The manned submersible is similar to unmanned submersibles with the exception of the means of signal and power transmission.

a] Components

The basic tethered self-propelled vehicle systems consists of the vehicle and sometimes the launcher,and a cable in addition to the control equipment on the surface.

b] Size

Existing submersibles range from very small sizes of less than 1 m in any direction to large ones up to 5 m .

c] Weight

The underwater vehicles vary in weight from 100 kg to as much as 2500 kg.

d] Operating Depth

Vehicles owned by the industry range in depth capabilities in the range of 200 m to 2000 m.

e] Speed

The speed of the unmanned vehicle ranges from 1 to 5 knots (0.5 - 2 m/sec).

f] Structure

Most vehicles consist of an open metal framework that supports and encloses, for protection its various components. Aluminium alloy is most widely used material because of light weight. Buoyancy is usually positive by a few newtons for fail safe operation.

g] Maneuverability

All but a few vehicles are capable of two translational motions and one rotational motion namely thrust (forward/reverse) and heave (up/down) and yaw (left/right heading changes) respectively. These motions are provided by two horizontal thrusters and one vertical thruster. The cable offers

an obvious potential for fouling, constraining the maneuvers.

h] Work Instrumentation

The primary task of the vehicle generally is observation and in many case photographic documentation .The submersibles are equipped with television cameras for viewing and photography respectively. The submersibles are provided with magnetic compasses, gyroscopes or inertial navigators for heading and position control. Acoustic sensors are also used in some cases for locating acoustically reflective targets. The equipment installed varies with the functions of the vehicles and the sophistication required.

1.1.6 Submersible Applications

The tasks performed by submersibles can be divided into two broad bases; inspection/documentation and manipulation. Most of the developed vehicles are used for inspection or documentation tasks. Very few vehicles have manipulative capabilities. Ocean engineering and oil industries are the two major areas in which submersibles are extensively used .They also ,find use in nuclear and hydroelectric power plants ,mainly for inspection tasks .

Under inspection the submersibles are primarily used for survey and photography of ocean beds ,survey of marine flora and fauna, identification and confirmation of historical wrecks.In power plants and oil industry submersibles are used for inspection of underwater structures and pipelines,for detecting deterioration and corrosion conditions .

In manipulative tasks they are used for search and retrieval of lost equipment on ocean beds ,cable and pipeline burial on sea beds , repair of pipelines , welding of underwater structures and for waste disposal on the ocean bed .It is also used for cleaning of underwater installations in power plants.

The submersibles can be used for host of other applications and the above list is about the accomplished tasks with them.

1.2 Objective and Scope of Present Work

1.2.1 Goal

The aim of the present work is to design an remotely controlled self propelled submersible vehicle to be used in nuclear spent fuel storage tanks.

High level waste in the form of spent fuels is stored in water ponds located at power plant site. The pond is generally about 40 m * 20 m * 15 m in size .Spent fuel from power plant is stored in these tanks till the activity drops to levels where fuel can be handled safely and without any radiation hazards during transport to fuel processing plants or for disposal.

The primary function of the vehicle is visual inspection of the tank and fuel rods .It will also be used for radiation level detection in the tank .

1.2.2 Rationale for the Use of Submersibles

The use of a submersible can be justified on the basis of improved safety regarding radiation exposure from spent fuel storage tanks .Visual inspection of fuel rods will reveal the

corrosion levels and the presence of external cracks on it. This is important, considering that failure of cladding will result in release of radioactive gases . It is also necessary to inspect tank walls since a damage to them will lead to seepage of radioactive water in the ground. The use of a submersible will lead to financial savings since it can be used to decide the inventory level of fuel stored in the tank .

1.2.3 Rationale for the Choice of Thesis Problem

At the end of this decade ,the biggest challenge faced by the nuclear industry is the unfavorable public opinion regarding its viability for electric power generation. The doubts fuelled by the TMI and the Chernobyll accidents, are related to the adverse effects of nuclear power plants on the environment and on human lives, during normal operation or accident situations.

To retain public trust for nuclear technology it is necessary to demonstrate beyond a certain doubt that nuclear power plants can be operated safely and with a minimum risk to human life. Advanced technologies will play a major role in building the necessary confidence and public acceptance for nuclear power plants.

It is generally recognized that development and the implementation of robotics and related systems have a significant impact on the safety and productivity of nuclear power plants. Minimization of personnel radiation exposure and reduction of plant outages are among the potential benefits of robots . Advanced systems will have to perform tasks that generate significant occupational radiation exposure and tasks that an be

performed reliably and in reduced time .

This motivated me to work on the development of a robotics system for nuclear power plants.

1.3 Design Requirements

To achieve the mission objective defined in section 1.2, the characteristics of the submersible to be designed can be ascertained. The characteristics given below will act as guidelines along which the submersible will be designed.:

a] The submersible should be unmanned. The hazardous nature of the nuclear installation rules out the choice of manned submersibles.

b] The submersible will be tethered in which the signal and power transmission medium is the umbilical and though it is cumbersome to manage it is preferred due to security of control. In case of untethered vehicle signal transmission could be by radio communication, optical signalling, or acoustic signally. Radio communication is limited by the predominance of metal structures giving rise to shadows which can lead to intermittence of communication. Optical signalling as a transmission medium for the present application is limited by the line of sight requirement. The signal media depending on acoustics is limited by the available bandwidth. The transmission of a single CC TV frame would take about one minute.[13]

c] The axial velocity of the vehicle should be in the range of 0.5 knots (0.25 m/sec) to 3 knots (1.5 m/sec)

d] The operating depth of the vehicle is limited to 20 m.

e] The vehicle should have high degree of maneuverability since it will operate in a confined space. The space between the fuel racks constrains the size of the vehicle to 1 m * 1 m * 1 m .

f] The submersible should move in the direction specified by the pilot.

g] The submersible must have high reliability. Any failure of vehicle should not result in loss in property or damage to the fuel rods.

h] In case of a power failure it should be possible to remove the vehicle manually from the tank. The vehicle should maintain its position and should not go out of control in a eventuality of power failure.

i] The vehicle should have ease of maintenance. The components should be in modules which can be easily dis-assembled.

1.4 Outline of the Thesis

The conditions the submersible should satisfy have been identified in section 1.3. The second chapter presents the design of the submersible. The third chapter investigates the forces acting on the vehicle and establishes the equilibrium conditions of the vehicle assuming steady state motion. The relationships for the calculations of forces are given in chapter-4. The guidelines for the selection of the propulsion system,the major element of the submersible is presented in chapter-5. Chapter-6 calculates the forces acting on the vehicle using equations established in chapter-4. The last but one chapter verifies whether the submersible meets the design requirements or

not. The last chapter sites the further work to be done on the vehicle.

CHAPTER II

SUBMERSIBLE DESIGN

2.1 Introduction

The design of the submersible, developed for the tasks mentioned in section-1.2 and satisfying the design requirements discussed in section 1.3 is presented in this chapter. The chapter gives the information of the designed vehicle and the related subsystems.

2.2 Submersible Specifications and Drawings

The sketch of the designed vehicle is shown in Fig 2.1 . The assembly drawings showing the components of the vehicle and the mounting arrangements is depicted in Fig. 2.2 [a],Fig. 2.2 [b] and Fig. 2.2[c] with the parts list given in Table. 2.1. The detail parts drawings are given in Fig.1 to Fig. 27 in Appendix-A. Fig.2[a] is the view of the vehicle from the stern side with the vehicle moving away from the viewer. Fig.2.2 [b] and Fig.2.2 [c] are the section drawings taken along the sections shown in Fig.2.2 [a].

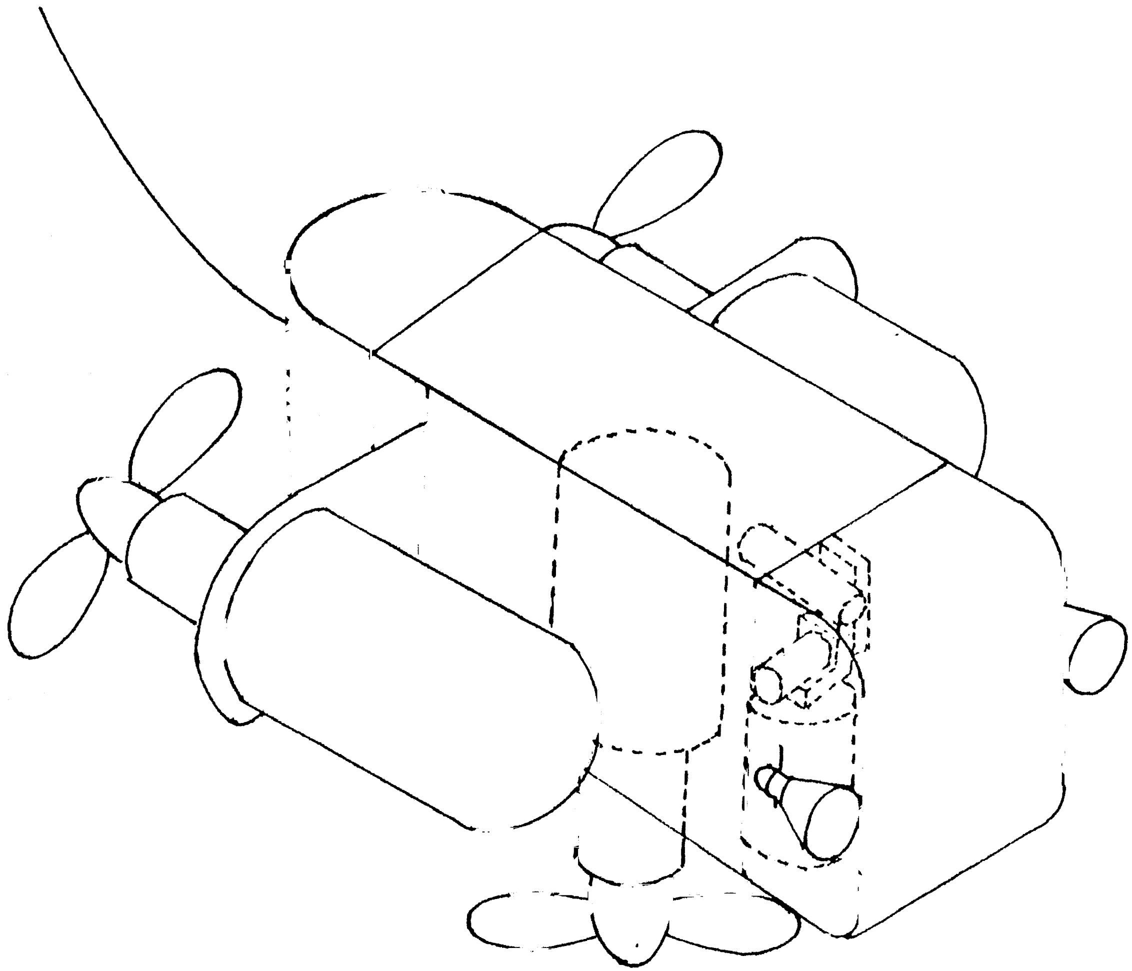
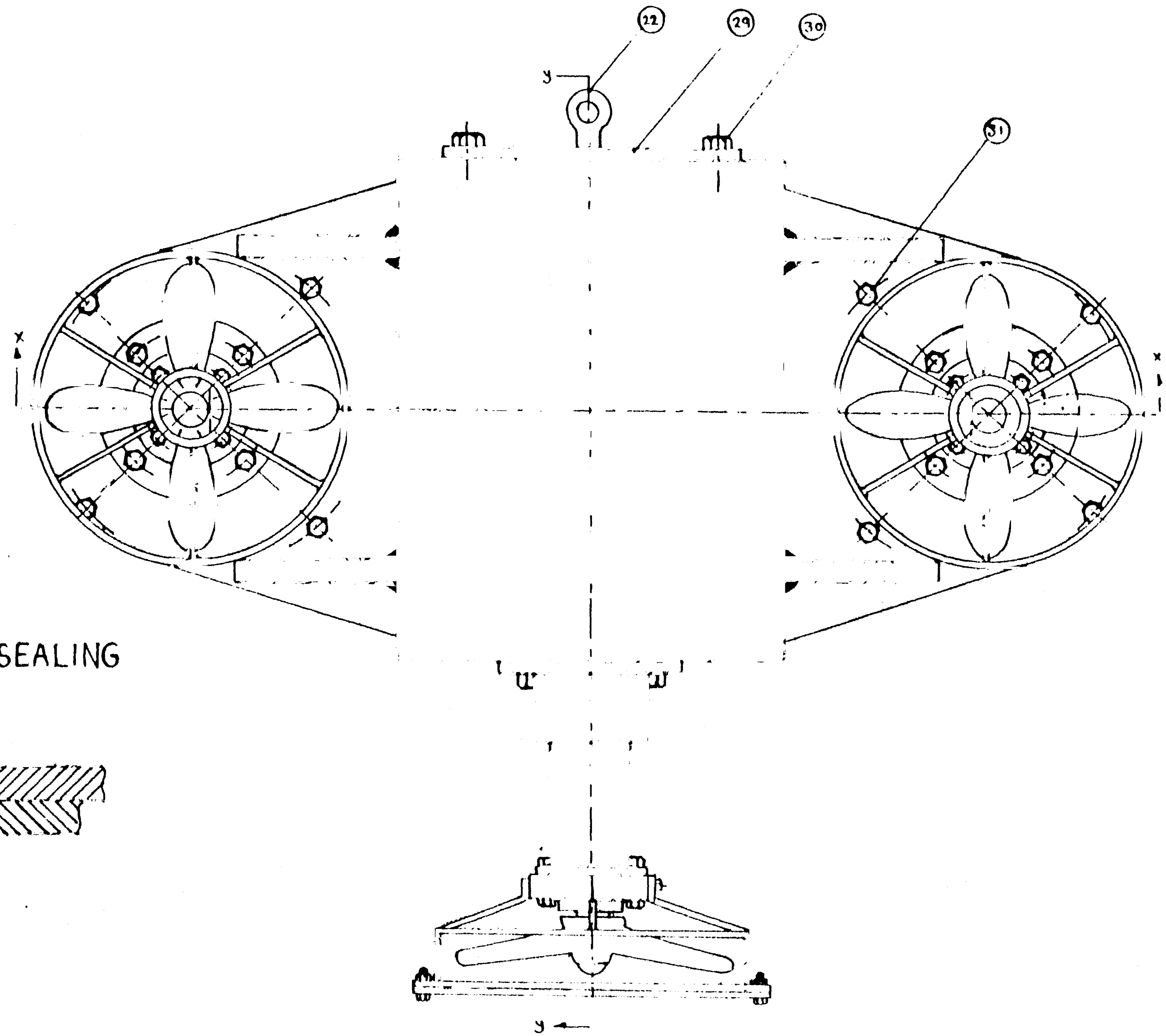


Fig. 2.1 Sketch of the Submersible



BOLT HOLE SEALING

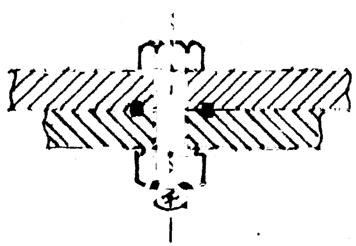
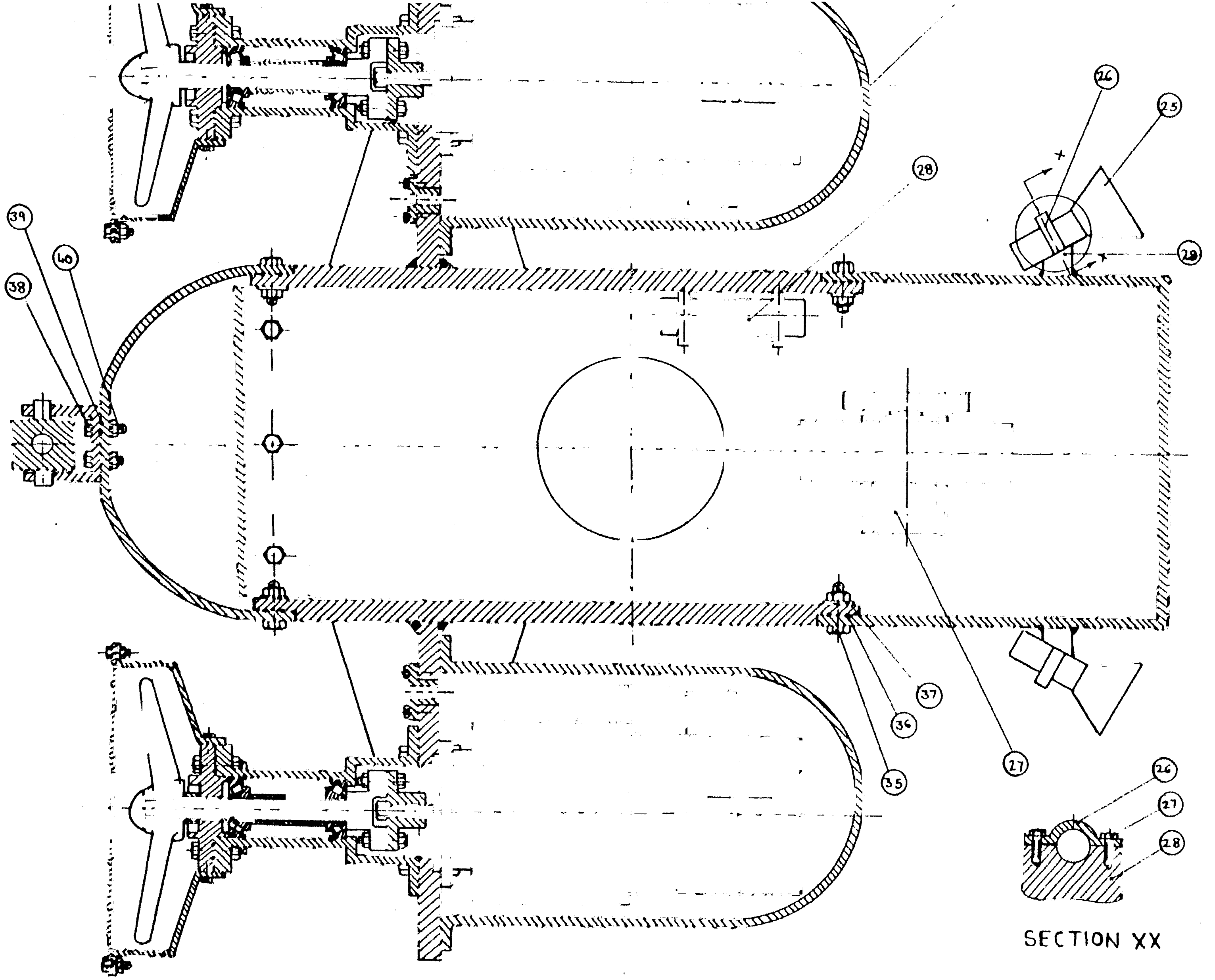


FIG 2.2a REMOTELY OPERATED UNDERWATER VEHICLE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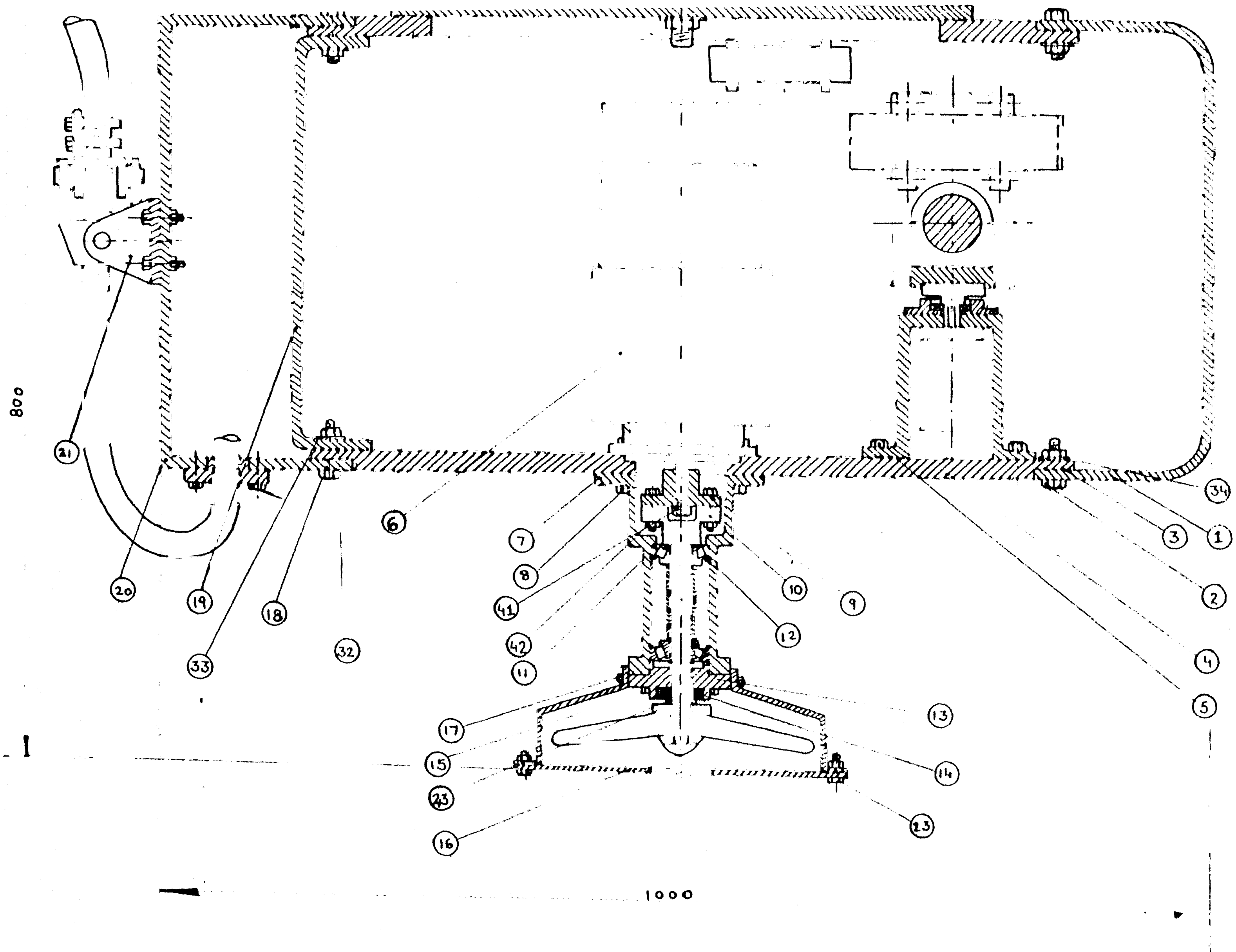


FIG. 2.2c. REMOTELY OPERATED UNDERWATER VEHICLE

No	Component	Material	Specification	No. Off	Fig No
1	Front Cover	Reinforced Plastic	-	1	2
2	Bolts for 1	-	M 16 * 2	6	Std
3	O ring for 2	-	i.d = 26 c/s ϕ = 4	6	Std
4	Buoyancy Tank	Al Alloy	-	1	1 a,b,c
5	Bolts for 27	-	M 16 * 2	4	Std
6	Motors	-	Yaskawa Hi-Cup D.C. Servomotor	3	Std
7	Shaft Cover	Al Alloy	-	3	6
8	Bolts for 7	-	M 8 * 1.25	4 * 3	Std
9	Shaft Extension	Al Alloy	-	3	9
10	Propeller Shaft	Al Alloy	-	3	10
11	Bearings	-		6	Std
12	Circlip	-	External i.d = 18	12	Std
13	Housing Cover	Al Alloy	-	3	13
14	Oil Seals	-	i.d = 30 o.d = 60	3	Std
15	Bolts for 13	-	M 8 * 1.25	4 * 3	Std
15 a	O ring for 15	-	i.d = 22 c/s ϕ = 3	4 * 3	Std
16	Shield	Al Alloy	-	-	-

No	Component	Material	Specification	No. Off	Fig No
17	Bolts for 16	–	M 6 * 1	4 * 3	Std
18	Bolts for 19	–	M 16 * 2	6	Std
19	Panel Board	Reinforced plastic	–	1	5
20	Back Cover	Reinforced plastic	–	1	3
21	Coupling	Al Alloy	–	1	2.3
22	Eye Bolt	–	M 20 * 2.5	1	Std
23	Propellers	Manganese Bronze	Table-1 in Appendix- B	3	–
24	Motor Cover	Al Alloy	–	3	2.4
25	Lights	–	Table - 5 in Appendix- B	2	–
26	Bracket for 25	Al Alloy	–	2 * 2	–
27	Mounting Bracket for 25	Al Alloy	–	2 * 2	–
28	Detector	–	GM Detector	1	–
29	Man Hole Cover	Al Alloy	–	1	5
30	Bolts for 29	–	M 16 * 2	6	Std
30 a	O rings for 29	–	i.d = 26 c/s ϕ = 4	6	Std
31	Bolts for 24	–	M 8 * 1.25	4	Std
31a	O rings for 31	–	i.d = 22 c/s ϕ = 4	4	Std

No	Component	Material	Specification	No. Off	Fig No
32	O ring for 8	-	i.d = 22 c/s ϕ = 3	4	Std
33	Washer for 18	-	i.d = 17	6	Std
34	Washer for 1	-	i.d = 17	6	Std
35	Bolts for 1	-	M 16 * 1.5	6	Std
36	O ring for 35	-	i.d = 26 c/s ϕ = 4	6	Std
37	Washer for 35	-	i.d = 17	6	Std
38	Bolts for 21	-	M 8 * 1.25	4	Std
39	O ring for 21	-	i.d = 22 c/s ϕ = 3	4	Std
40	Washer for 21	-	i.d = 9	4	Std
41	Bolts for 9	-	M 8 * 1.25	4	Std
42	Nut for shaft	-	M 8 * 1.25	3	Std
43	Washer at hub	-	i.d = 25	3	Std

Table. 2.1 Parts List of the Submersible

The overall dimensions of the vehicle is given in Table 2.2 and Table 2.3 gives the vehicle specifications .

No	OVERALL DIMENSIONS		Value
1	Length	(m)	1.0
2	Breadth	(m)	1.0
3	Height	(m)	0.8

Table. 2.2 Overall Dimension of the Submersible

No	SPECIFICATIONS		VALUE
1	Weight	(N)	1810
2	Depth	(m)	0 - 20
3	Forward Velocity	(m/sec)	0 - 1.0
4	Vertical Velocity	(m/sec)	0 - 0.7
5	Forward Thrust	(N)	0 - 200
6	Vertical Thrust	(N)	0 - 130
7	Power Required	(W)	1000

Table. 2.3 Submersible Specifications.

2.3 Details of the Designed Submersible

2.3.1 Hull Assembly

The submersible has a closed framework metal structure so that water tight sealing for individual vehicle components is not required. The hull assembly consists of the buoyancy tank, the front cover, the back cover and the manhole cover and the panel board for electric connections, shown in Fig.1 a,b and c, Fig. 2, Fig.3, Fig.4 and Fig.5 respectively,attached in Appendix - A. The buoyancy tank acts as a support for the vehicle components and provides the required buoyancy. The tank is made of an aluminium alloy since it has high strength to weight ratio, and corrosion resistance. The observation port of the vehicle is the the front cover of the hull. This is made of an unsaturated polyester with reinforcing material like glass fibre which is transparent, has high weight to strength ratio, high rigidity, high impact resistance and a high chemical resistance. For the vehicle to maintain its upright position at rest, the distribution of weight must be uniform. The rear of the hull that is the back cover is also made of the same material. The hull has a manhole to facilitate easy assembly and dis-assembly of the components.

The front cover is not streamlined since it would have acted as a lens affecting observation. The back cover is given a cylindrical shape so as to reduce turbulence in the wake region.

The bolt hole sealing is achieved by use of o-rings around each hole and a copper washer as shown in Fig. 2.2 [a]. The copper washers for the bolt holes of front and back cover can be substituted by washers of softer material.

2.3.2 Thruster assembly

The thruster assembly and the propeller configuration is shown in Fig. 2.2 [a], [b] and [c]. The details of the thruster assembly is given in Fig. 6 to Fig. 11 inAppendix-A The vehicle is equipped with two horizontal screw propellers providing thrust for motion in the forward and reverse direction and the yaw couple for left or right heading changes. A third degree of freedom in the up or down direction is provided by a screw propeller acting along the vertical axis. The propeller specifications are given in Table 1 in Appendix- B. The propeller is driven by a D.C servo motor, the specifications of which are given in Table 2 in Appendix B. D.C servo motors provide excellent speed regulation, and high torque and therefore they are ideally suited for control applications. The motors selected are of the Yaskawa make . It is a smooth core armature type servo motor consisting of a hollow, cup shaped armature and permanent magnets of salient pole construction. The motor is flange mounted with totally equipped self cooled enclosure. The speed of the motor is controlled by the manipulation of the D.C. motor voltage. The motor will draw whatever current is required to overcome the torque. The feedback of the motor speed is through a D.C tachometer. A magnetic brake is used for braking. The operator has to guide the vehicle by using twin axis joy sticks. The block diagram showing the control elements is given in Fig. 2.3.

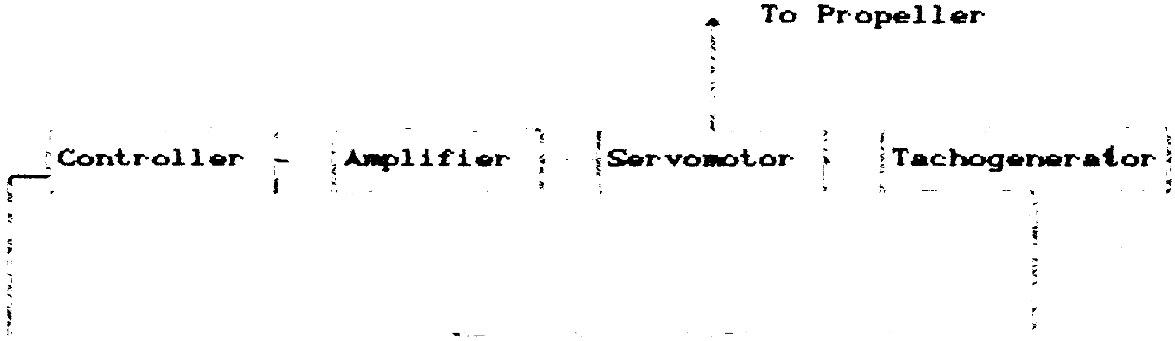


Fig. 2.3 Elements of Control loop.

2.3.3 Camera Assembly

The submersible is provided with a C.C.D camera for observation, mounted on a pan and tilt mechanism. The camera is of the Pulnix make, the specifications of which are given in Table-3 in Appendix- B. The camera has a high resolution (250 * 350 lines) ,is light in weight (0.7 Kg), and it can operate with a minimum illumination of 3 Lux .

The camera is mounted on a pan and tilt mechanism. The proposed design for the mechanism is shown in Fig.2.4 and the parts list is given Table - 2.4. The details of the componentsis given in Fig.12 to Fig.17 attached in Appendix-A .The pan and tilt mechanism specifications are given in Table - 4 in Appendix-B. Two stepper motors provide the 2 degrees of freedomin the horizontal and the vertical axis. Stepper motors are used since the torque required is small and the motors will provide motion in steps for indexing the camera through the required angle. The available freedom in pan motion (vertical

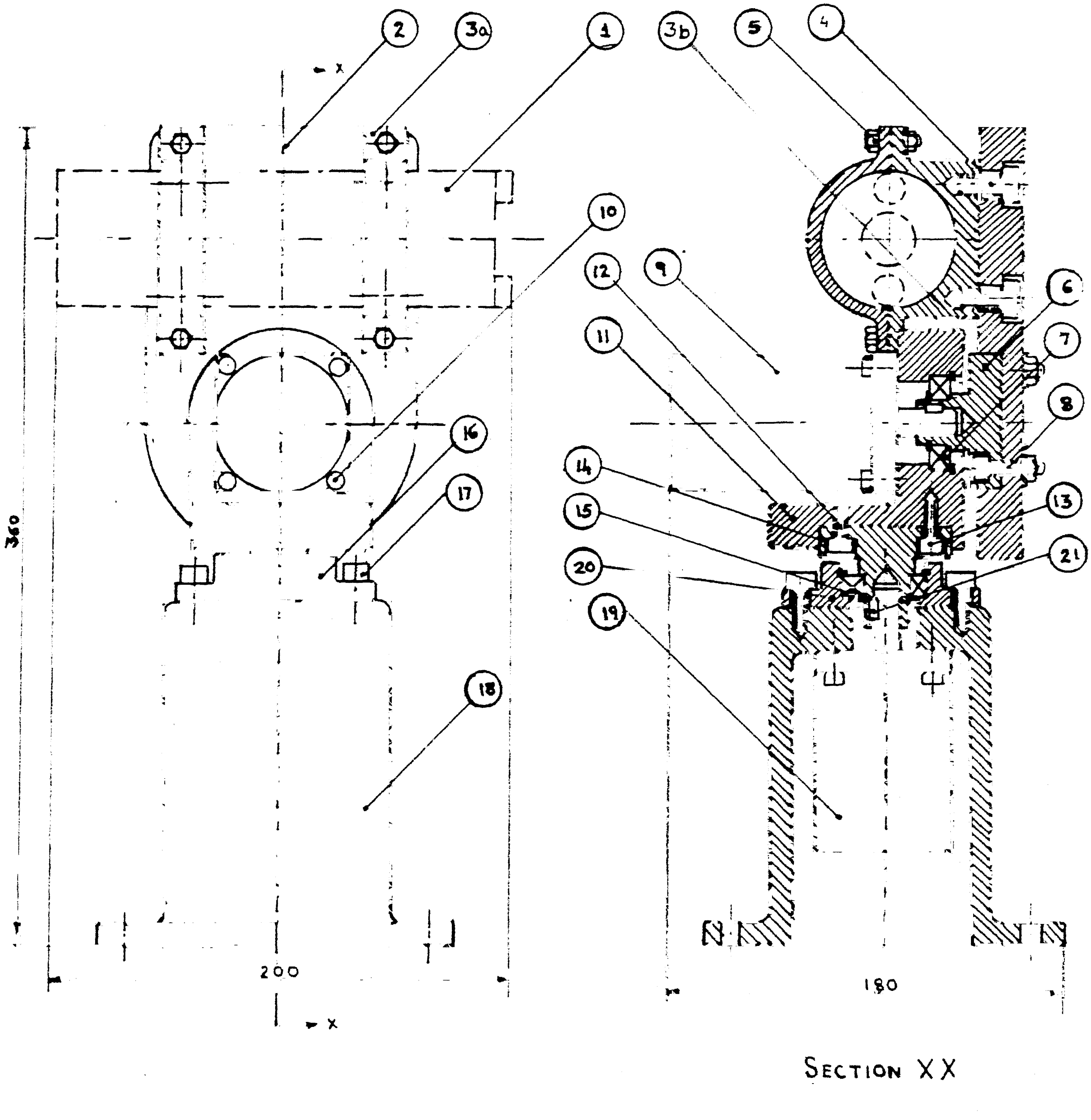


Fig. 2.4 Pan & Tilt Mechanism

No	Component	Material	Specification	No. Off	Fig No
1	Camera	-	Table - 3 in Appendix - B	1	-
2	Camera base	Al Alloy	-	1	12
3a	Bracket for 2	Al Alloy	-	2	18a
3b	Mounting Bracket for 2	Al Alloy	-	2	18b
4	Allen Bolts For 2 & 3a	-	M 8 * 1.25	2	Std
5	Bolts for 3a,b	-	M 6 * 1.0	2	Std
6&14	Shaft Extension	Al Alloy	-	2	16
7&15	Deep Groove Ball bearings	-		4	Std
8	Allen Screws	-	M 6 * 1.0	4	Std
9&19	Stepper Motors	-	Table-4 in Appendix- B	2	Std
11	Revolving Base	Al Alloy	-	1	11
12	Allen Screw for 11	-	M 8 * 1.25 l = 15	2	Std
13	Allen Screw for 11	-	M 8 * 1.25 l = 25	2	Std
16	Bearing Housing	Al Alloy	-	1	15
17	Allen Screw for 16	-	M 8 * 1.25	4	Std
18	Fixed Base	Al Alloy	-	1	14
20	Circlips	-	i.d = 20	4	Std

No	Component	Material	Specification	No. Off	Fig No
21	Key	-	t = 8 w = 8	2	Std
10	Back Cover	Reinforced Plastic	-	1	3 in App - A

Table 2.4 Parts List for Pan and Tilt Mechanism

axis) is 180° while that in tilt (horizontal axis) is 270°. The motor specifications are given in Table - 5 in Appendix - B.

The camera is so mounted that it's centre and the mechanism centre coincide. The pan and tilt mechanism is positioned in the hull, such that the hull centreline and the mechanism centreline coincide as shown in Fig 2.2 [a] and [b]. The position of the camera can be read from position encoders calibrated to give direct reading, with the vehicle centreline acting as the reference line. The camera is guided by the operator using a joy stick .

2.3.4 Lights Assembly

The submersible is provided with two high intensity, underwater incandescent lights of 100 W capacity and a average life of 200 hr. Together the lights will enable taking images up to a distance of 4 m from the camera. The lights are small in size, simple and start instantaneously. The specifications of the lights are given in Table - 6 in Appendix - B. The lights are mounted on the outside of the hull to facilitate easy removal. They are offset to the line of sight of the camera so that scattering of light within the volume of water common to both the illuminating and the sensing systems is eliminated. This will give a better quality of image at long distances.[24]

2.3.5 Cable and the Cable Winch Assembly

The power and signal transmission to the submersible is via a cable which is wound on a winch placed at the surface. The typical cable consists of a centre core of

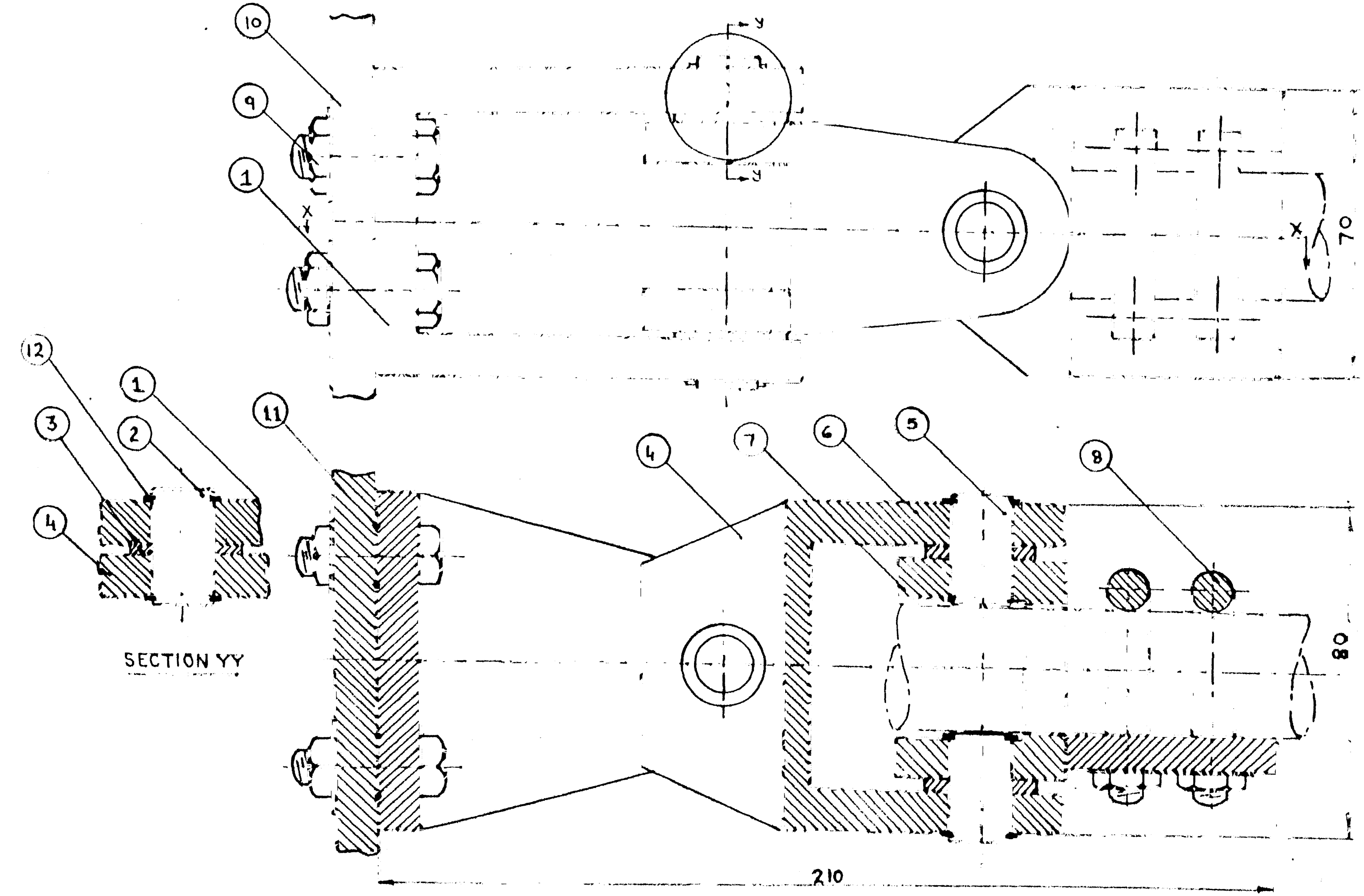


FIG. 2.5 CABLE COUPLING

No	Component	Material	Specification	No. Off	Fig No
1	Fixed Bracket	Al Alloy	-	1	18
2&5	Pin	Al Alloy	-	4	21
3	Washer	-	i.d = 20	4	Std
4/6	Connector	Al Alloy	-	1	19
7	Bracket for cable	Al Alloy	-	1	20
8	U- Clip	Al Alloy	-	2	22
9	Bolts for 1	-	M 16 * 1.5	4	Std
10	O ring for 9	-	i.d = 26 c/s ϕ = 4	4	Std
11	Washer	-	i.d = 17	4	Std

Table. 2·5 Parts List of Coupling

conductors, an insulating jacket,an electric or magnetic shield, a protective armor and an outside cover made of rubber or thermoplastics.[15] The cable diameter will be about 30 mm .

The cable is connected at the rear end of the vehicle on the back cover through a coupling giving two degrees of freedom. The coupling assembly drawings are shown in Fig.2.5,with the parts list given in Table - 2.5 and the parts drawings are shown in Fig.18 to 22 in Appendix - A .The cable enters the hull and all the electrical connections can be made on the panel board mounted in the hull.

The proposed design of the cable winch is shown in Fig.2.6 and Fig.2.7. Fig.2.6 is the sketch of the cable winch while Fig.2.7 is the assembly drawing. Table. 2.6 is the parts list for the cable winch . The detail drawings are given in Fig.23 to Fig.27 in Appendix - A .

The cable is stored on the drum of a diameter around 300 mm. The diameter of the drum should be more or equal to eight times that of the cable[15] diameter. One end of the cable passes over a pulley .The pulley is provided so that the cable does not touch the sides of the tank. The other end of the cable is taken out through the centre of the drum. The cable has to pass through slip rings before it is connected to the control console.

The cable drum is driven by a D.C motor so that the vehicle does not have to pull the cable. As the vehicle moves away from the cable the motor drives the drum so that the tension never exceeds a preset value which may be 10 N. A drop in cable tension results in cable overhang increasing the probability of cable fouling. The motor may stop releasing the cable at an tension

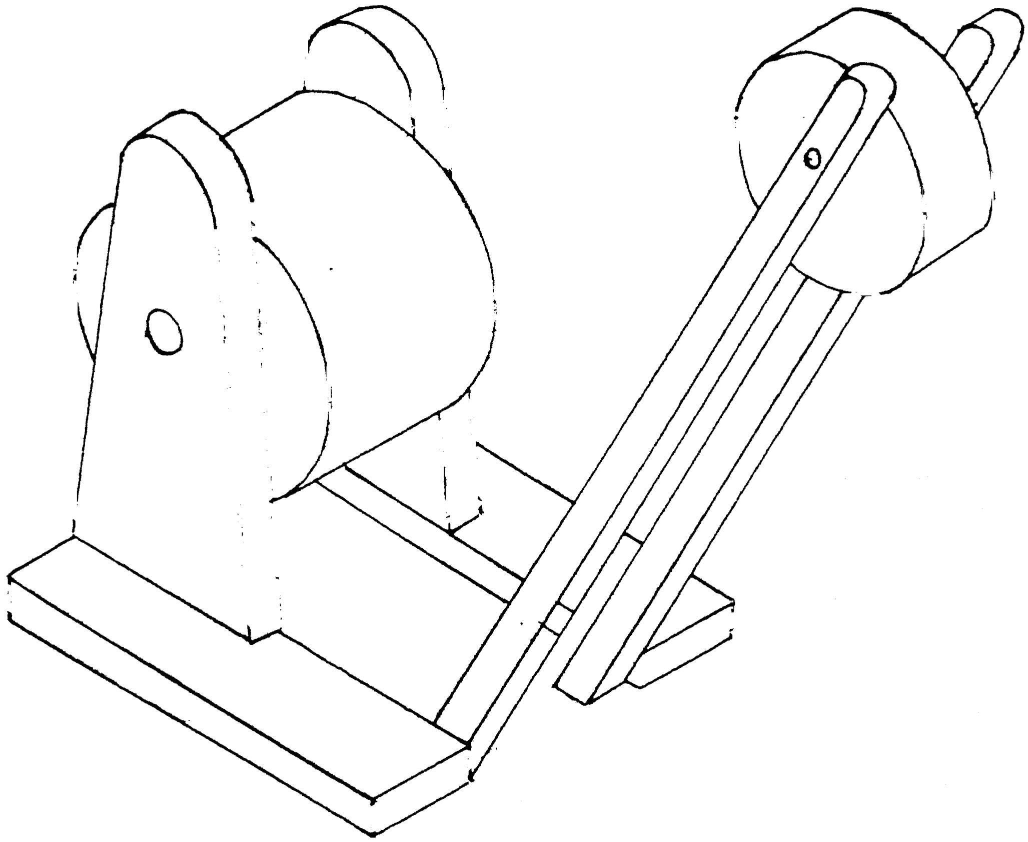


FIG. 2.6 SKETCH OF CABLE WINCH

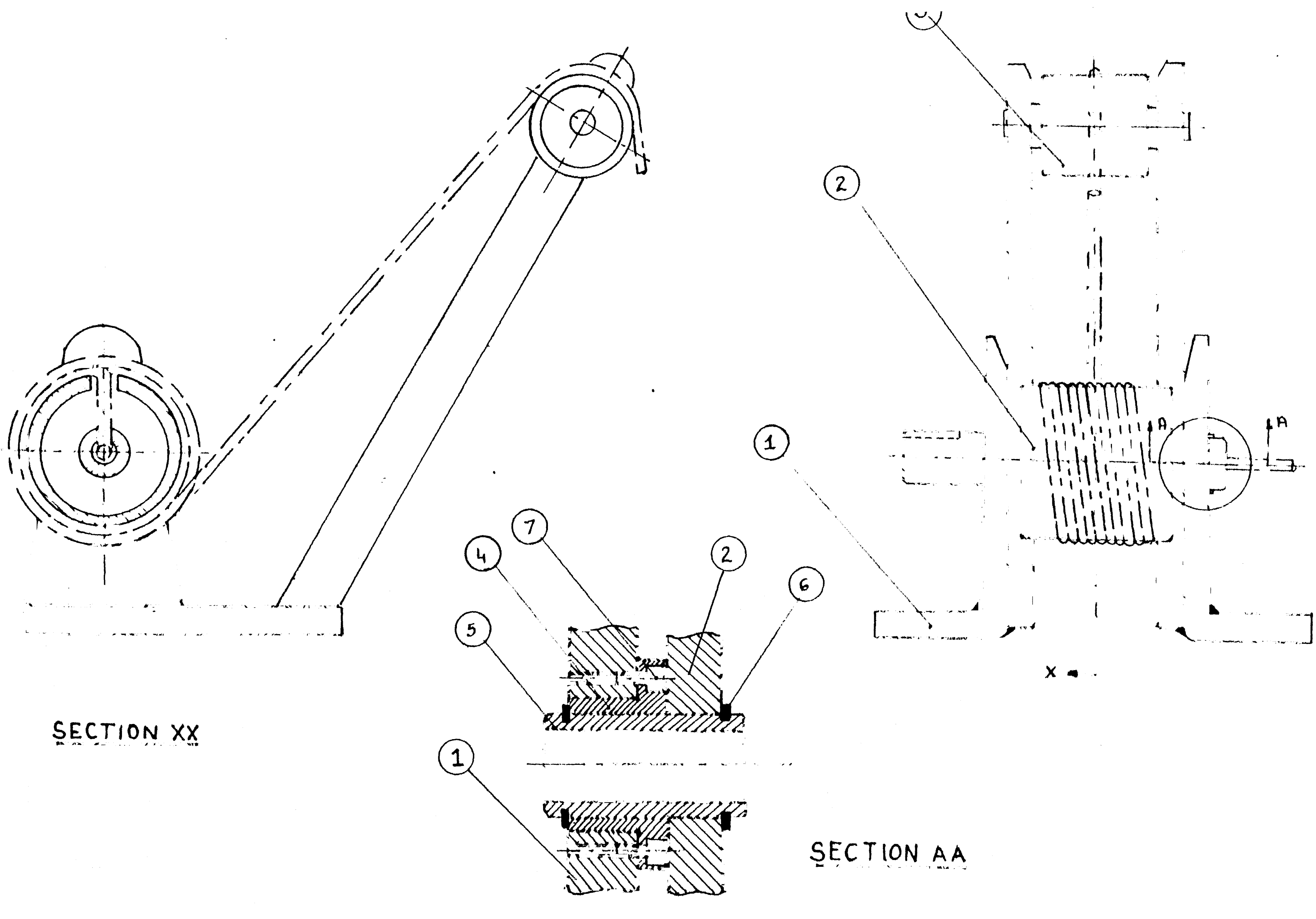


Fig. 2.7 Cable Winch

No	Component	Material	Specification	No. Off	Fig No
1	Winch base	M.S	–	1	23
2	Drum	M.S	–	1	24
3	Pulley	M.S	–	1	26
4	Bush	Phospher Bronze	–	2	25
5	Shaft	Alloy Steel	–	2	27
6	Circlip	–	External i.d = 40	4	Std
7	Allen Screw for 4	–	M 10 * 1.25	4 * 2	Std

Table. 2.7 Parts list for Cable Winch

value of around 5 N

When the vehicle is moving towards the pulley the motor rotates in opposite direction winding the cable. In this case a lower tension in the cable is detrimental (refer to section-6.2.3), and the motor starts winding the cable at the lower value of 5 N and stops at 10 N.

The motor speed for forward motion may be set at 60 rpm so that more cable is released than required, to keep the tension in the cable to a minimum. On the other hand the motor speed for reverse motion may be 50 rpm so that the cable taken up is less than the required length and there is some overhang in it. The torque rating of the motors may be 7.5 Nm with a power capacity of 50 W.

2.3.6 Navigation Instruments

The navigation aids for assisting the pilot along with the camera are the, magnetic compass to give remote reading of the vehicle heading,pressure transducer giving depth information, read by the operator from a digital meter and echo sounders for obstacle avoidance. The camera aids the operator in knowing where his vehicle is with reference to the tank walls or with reference to the racks which are numbered. The magnetic compass enables the operator to guide his vehicle in the desired direction. The echo sounders aid obstacle avoidance by giving signals when the vehicle nears the object. The vehicle can be conveniently maneuvered using these simple sensors. Further sophistication ,if required ,can be provided by using acoustic sensors to give the x,y,z coordinates of the vehicle.The vehicle

can also be equipped with velocity sensors if necessary.

2.3.7 Radiation Detection Device

The submersible is provided with a Geiger - Mueller detector for measurement of radioactivity level in the tank. The detector will give the total radiation level. The detector gives the radiation in a digital form as no of counts in a time period. It is used since it is suitable for any type of radiation. In addition, it has a large output pulse and has a rugged construction.

CHAPTER III

STEADY STATE FORCE ANALYSIS

3.1 Introduction

To determine whether the submersible is capable of moving at a required velocity in a specified direction, maintaining it's ,upright position, it is necessary to investigate the forces which will act on it. The following sections determine the equilibrium conditions for the vehicle moving with a steady velocity and when it is at rest. Although steady motion of a marine vehicle is an ideal situation which cannot be achieved in practice, the simplification has been made owing to the complex behavior of the flow about the vehicle.

3.2 Terminology

Some commonly used terms for submersibles are defined[2] below with reference to Fig 3.1 :

a) Surge : Motion of the vehicle along the X-axis which extends from the bow to the stern,lying in the principal planes of

transverse and vertical symmetry.

b] Sidle : Motion of the vehicle along the Y - axis which is perpendicular to the X-axis and lies in the principal plane of transverse symmetry.

c] Heave : Motion of the vehicle along the Z - axis,mutually perpendicular to the X and Y axis.

c] Roll : Rotation of the vehicle about the X - axis .

d] Pitch : Rotation of submersible about the Y - axis .

e] Yaw : Rotation about the Z - axis .

3.3 Forces Acting on the Submersible at Rest

Consider a stationary,axisymmetric submersible with the longitudinal section shown in a fluid of infinite extent which is at rest. The submersible is acted upon by two forces; the buoyant force (Fa) resulting from the distribution of static pressure over the surface of the vehicle and the weight (W)of the submersible. The equilibrium condition with refernce to Fig. 3.2 is :

$$W = F_a \quad \text{.......................................(3.1)}$$

Since weight and the buoyant force are the only forces acting on the vehicle, the centre of buoyancy (B) should be vertically above the centre of gravity (G) . To study the effect of small angles of rotation we can rotate the vehicle about the horizontal axis. Consider the submersible represented in Fig 3.2. It is evident that if point B is above point G, a angular rotation

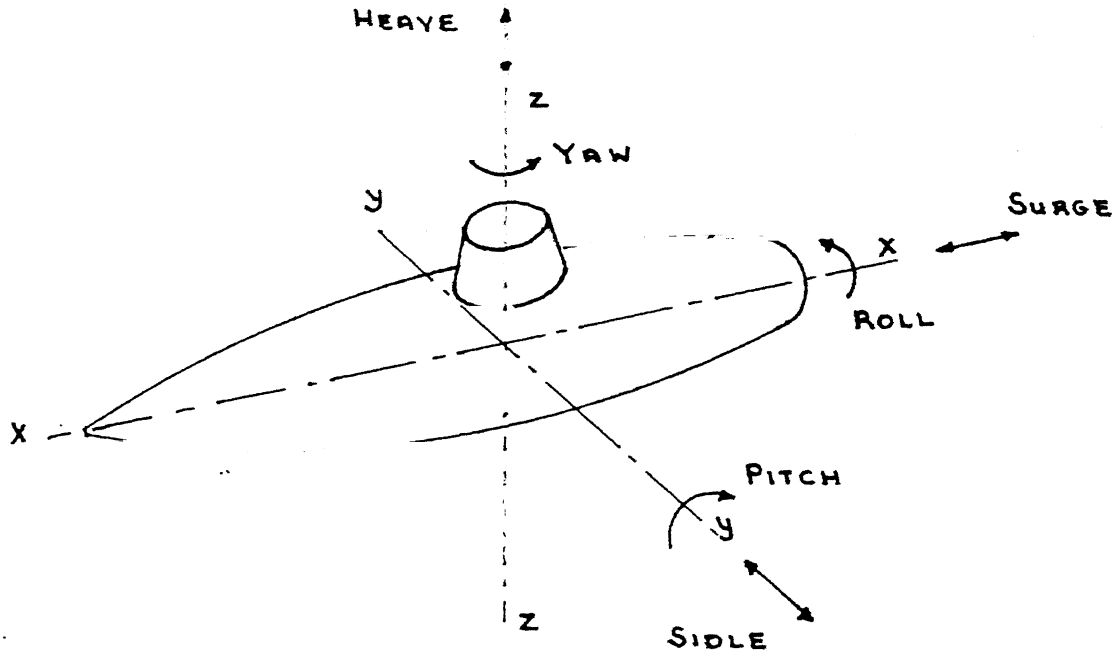


FIG. 3.1 MOTION REFERRED TO VEHICLE AXIS

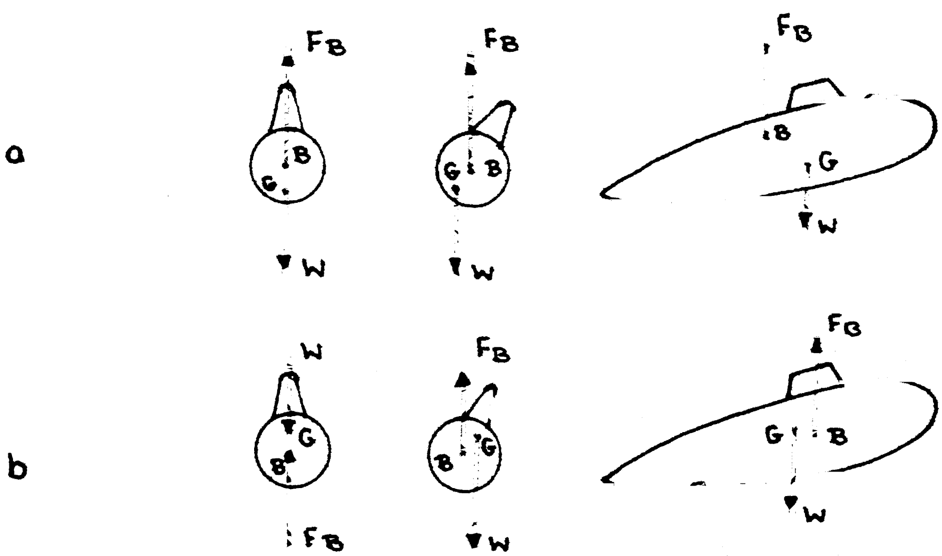


FIG. 3.2 STATIC EQUILIBRIUM

produces a righting couple and a hydrostatically stable system. By contrast the arrangement in Fig 3.2 (b) shows that if B is below G then a small inclination has a tendency to increase, and so the vehicle is unstable. If the two points coincide then the system is neutrally stable. The distance GB is a measure of submarine hydrostatic stability for roll or pitch.

3.4 Forces Acting on the Vehicle during Steady State Motion

3.4.1 Surge Motion

Suppose the designed submersible moves in the forward direction at an steady velocity V by the application of propulsive forces T_{x1} and T_{x2} by the two horizontal propellers (P_1 and P_2) as shown in Fig. 3.3. The forces acting on the vehicle are also shown in the same figure along with the notations. The flow pattern about the vehicle can be assumed to be axisymmetric so that the forces normal to the direction of velocity resulting from any modification of pressure distribution will cancel out. The fluid dynamic force lift is therefore zero and only the buoyant force acts on the vehicle, which remains constant. The vehicle is subjected to a drag force (D_{x1} and D_{x2}) and the cable forces (t_{cx}, t_{cy}, t_{cz}). The expressions for calculating these forces is given in chapter - 4 and the last chapter verifies if the conditions are satisfied or not.

For the vehicle to be in equilibrium , the sum of the forces and the moments in all directions should be zero. The equilibrium conditions are written using this criterion and with the assumption that vehicle is neutrally buoyant and is positively

SURGE MOTION

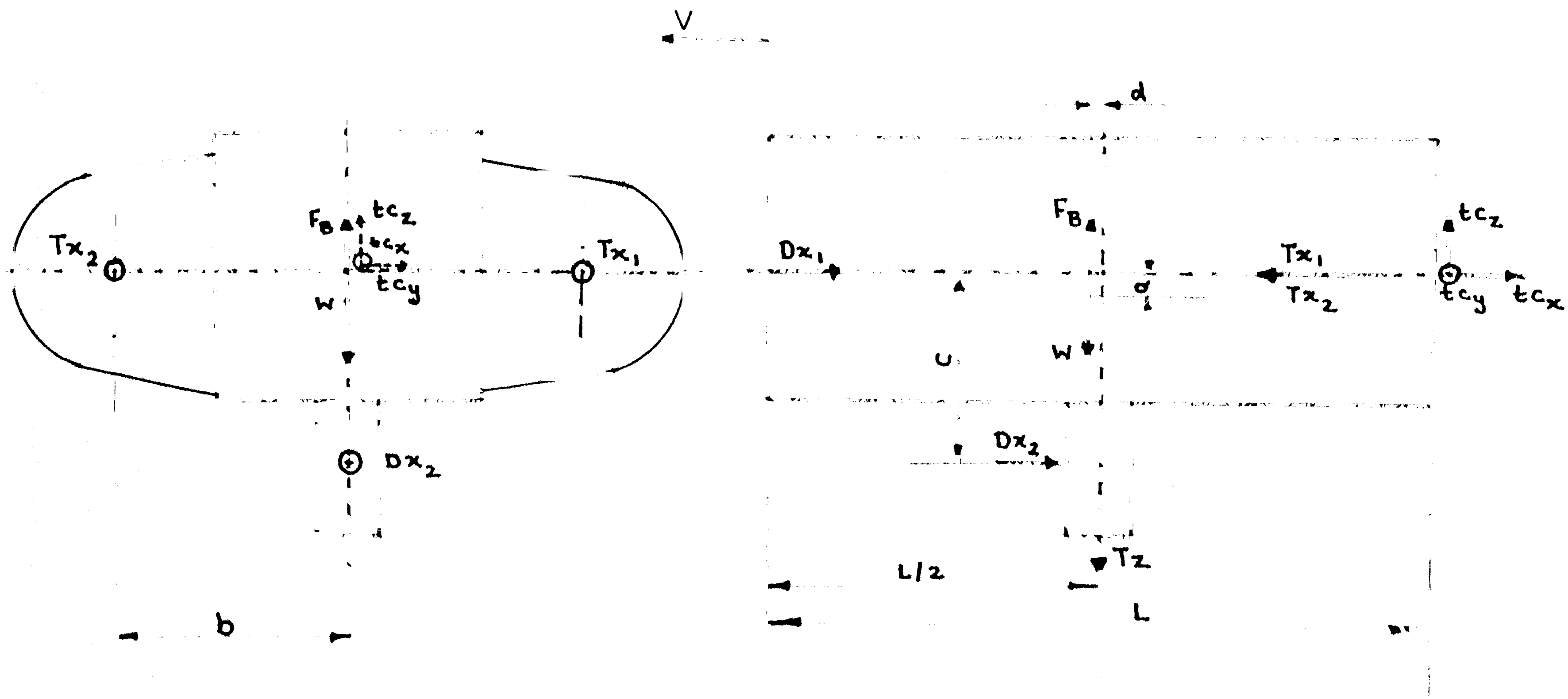


FIG. 3.3 F.B.D OF SUBMERSIBLE

stable under the action of hydrostatic forces.

$$\Sigma\, F_x = T_{x1} + T_{x2} - D_{x1} - D_{x2} - t_{cx} = 0 \quad \ldots(3.2)$$

$$\Sigma\, F_y = t_{cy} = 0 \quad \ldots(3.3)$$

$$\Sigma\, F_z = t_{cz} - T_z = 0 \quad \ldots(3.4)$$

$$\Sigma\, M_x = 0 \quad \ldots(3.5)$$

$$\Sigma\, M_y = t_{cz} * L/2.0 + D_{x2} * c = 0 \quad \ldots(3.6)$$

$$\Sigma\, M_z = t_{cy} * L/2.0 - b * (T_{x1} - T_{x2}) = 0 \quad \ldots(3.7)$$

3.4.2 Heave Motion

Fig 3.4 shows the forces acting on the vehicle moving in the vertical direction under the action of a propulsive force T_z applied by the propeller P_3. The vehicle is subjected to a vertical drag force (D_z) and the cable forces (t_{cx}, t_{cy}, t_{cz}). The equlibrium conditions can be written referring to Fig 3.4.

$$\Sigma\, F_x = T_{x1} + T_{x2} - t_{cx} = 0 \quad \ldots(3.8)$$

$$\Sigma\, F_y = t_{cy} = 0 \quad \ldots(3.9)$$

$$\Sigma\, F_z = T_z - t_{cz} - D_z = 0 \quad \ldots(3.10)$$

$$\Sigma\, M_x = 0 \quad \ldots(3.11)$$

$$\Sigma\, M_y = t_{cz} * L/2.0 = 0 \quad \ldots(3.12)$$

$$\Sigma\, M_z = (T_{x1} - T_{x2}) * b = 0 \quad \ldots(3.13)$$

3.5 Conclusions

The forces acting on the vehicle have been identified and the equilbrium conditions have been established. The next chapter deals with the methodology to calculate the above forces. Chapter- 6 provides the force calculations and Chapter-7 investigates the equlibrium conditions.

HEAVE MOTION

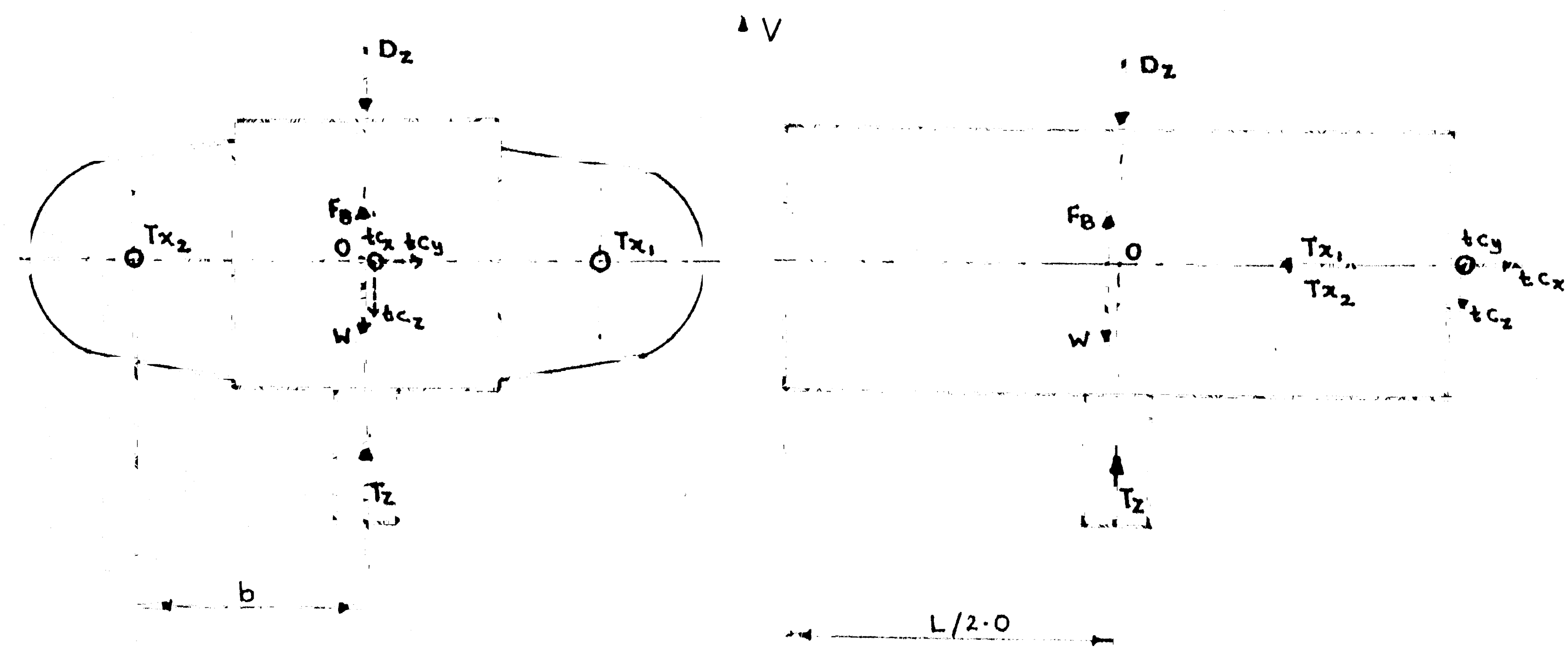


FIG. 3.5. F.B.D OF SUBMERSIBLE

CHAPTER IV

METHODOLOGY FOR FORCE CALCULATIONS

4.1 Introduction

In the previous chapter the forces acting on the vehicle have been identified. This chapter establishes the expressions and the method followed to calculate these forces. The calculations of the forces are presented in section 6.2. The following are the notations used for force calculations :

A	:	Projected Area of the vehicle perpendicular to the direction of motion.
C_d	:	Normal drag coefficient.
C_t	:	Tangential skin friction drag coefficient.
D	:	Drag force on the vehicle (N).
D_r	:	Normal pressure drag on the cable (N).
D_t	:	Tangential skin friction drag on the cable (N).
F_B	:	Buoyant Force on the vehicle. (N)
$\hat{F}$	:	External Force such as drag forces and buoyancy forces acting on the cable. (M/m)
l	:	Total length of cable (m)
l,m,n	:	Direction cosines at any point on cable.

$\hat{r}$: Position vector of any point on the cable (x.i + y.j + z.k)

s : Cable length at a point with position vector $\hat{r}$.

t : total tension in the cable (N).

tcx,tcy & tcz : Component of tension t in the x,y,z coordinates

$\hat{U}$: Velocity vector for the cable Ux.i + Uy.j + Uz.k

ρ : Density of the fluid (Kg/m^3)

Δ : Displaced volume (m^3)

4.2 Expression for Calculating Hydrostatic Forces

The hydrostatic forces acting on the vehicle are the buoyant force and the weight. The weight of the vehicle can be calculated by adding the weight of the vehicle components. The buoyant force is given by the expression :

$$F_B = \rho * g * \Delta \quad \text{.....................................(4.1)}$$

4.3 Expression for Calculating Drag Force

The vehicle is subjected to a drag force parallel to the direction of velocity resulting from the distribution of shear stress over the vehicle surface. The drag of non lifting bodies is composed of two parts ; the form drag or the pressure drag and the skin friction drag. The form drag is the resultant stream wise component of fluid pressure forces over the body

surface, while the skin friction drag is the resultant of shearing stresses.

The drag of bluff bodies (non streamlined) is primarily due to form drag, since boundary layer separation produces large wake. On the other hand a streamlined body is so shaped that it does not experience large, adverse pressure gradients. The wake is small and the skin friction drag is the predominant drag force.

Since the vehicle is a bluff body the drag force is calculated by the fundamental law given by the expression[25]:

$$D = 0.5 * \rho * C_d * A * V^2 \quad \ldots\ldots\ldots\ldots(4.2)$$

4.4 Cable Forces

4.4.1 Drag Force on cable

Consider the free body diagram of the cable given in fig 4.1. The cable is subjected to the following forces ; the tension at the two ends of the cable (T_1 and T_2), the weight (W_c), the buoyant forces (Fc_B) and the drag forces (D_p and D_f) due to the velocity of the cable.

The drag force on a element of a cable of length dl, moving with a velocity U and making an angle Ø with the horizontal is given as[19]:

$$D_p = 0.5 * \rho * C_d * d * \sin^2 \emptyset \quad \ldots\ldots\ldots\ldots(4.3)$$

$$D_f = 0.5 * \rho * C_l * d * \cos^2 \emptyset \quad \ldots\ldots\ldots\ldots(4.4)$$

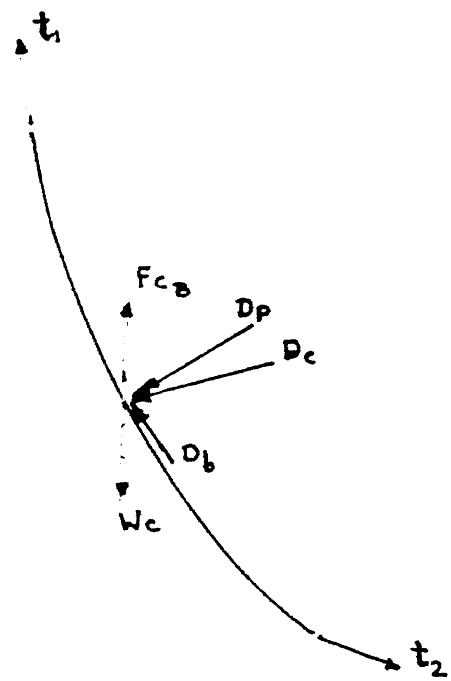


FIG. 4.1 CABLE FORCES

These expressions are for a cable moving in the same plane as that of the direction of motion. Similar expression can be written for a 3-D problem as[2] :

$$\hat{D}_p = F_o * \left[\hat{U} - \left\{ \hat{U} . \frac{d\hat{r}}{ds} \right\} * \frac{d\hat{r}}{ds} \right] \quad \ldots\ldots\ldots\ldots(4.5)$$

where

$$F_o = 0.5 * \rho * C_d * d \left[\hat{U}^2 - \left\{ \hat{U} . \frac{d\hat{r}}{ds} \right\}^2 \right]^{1/2} \quad \ldots\ldots(4.6)$$

$$\hat{D}_f = 0.5 * \rho * C_t * d * \left\{ \hat{U} . \frac{d\hat{r}}{ds} \right\}^2 * \frac{d\hat{r}}{ds} \quad \ldots\ldots(4.7)$$

Substituting $\hat{U} = U_x\, i + U_y\, j + U_z\, k$ and

$$\frac{d\hat{r}}{ds} = l\, i + m\, j + n\, k$$

in equation 4.5, 4.6, and 4.7 they can be written as :

$$\hat{D}_p = F_o\, [\, (U_x, U_y, U_z) - (\, l.U_x + m.U_y + n.U_z\,).(\, l, m, n\,)\,]$$

$$\ldots\ldots\ldots\ldots\ldots\ldots(4.8)$$

$$F_o = 0.5 * \rho * d * C_d \left[(U_x, U_y, U_z)^2 - (l.U_x + m.U_y + n.U_z)^2 \right]^{1/2}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots(4.9)$$

$$\hat{D}_f = 0.5 * \rho * d * C_t * \left[(l.U_x + m.U_y + n.U_z)^2 \right] (\, l, m, n\,)$$

$$\ldots\ldots\ldots\ldots\ldots\ldots(4.10)$$

4.4.1 Cable Tension

In order to calculate the drag forces and the tension in the cable it is essential to know the cable configuration. The equilibrium condition for the cable is given by the equation :

$$\frac{d\,[\,t\,d\hat{r}/ds\,]}{ds} + \hat{F} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots(4.11)$$

The equation given above is valid for the following assumptions :

a] Cable stretching is neglected. Elongation of the cable is significant at long scopes . The length of the cable for this problem is limited to maximum of 25 m ,so the assumption is justified.

b] Inertial forces are neglected.

c] The cable is assumed to be subjected to only normal drag forces. The tangential drag force is significant only at long scopes. The ratio of normal drag coefficient to tangential drag coefficient C_d/C_t is normally taken as 0.02 . In comparison to the magnitude of the normal drag force the magnitude of tangential drag force is very small .

d] The cable is assumed to be neutrally buoyant .

e] Cable stiffness is neglected. It is assumed that cable cannot support any bending moments.

Equation (1) can be rewritten as :

$$\frac{dt}{ds} \cdot \frac{d\hat{r}^2}{d^2s} + t \cdot \frac{d\hat{r}^2}{d^2s} + \hat{F} = 0 \quad \ldots\ldots\ldots(4.12)$$

Dot product of equation (4.12) with $d\hat{r}/ds$ gives the equation :

$$\frac{dt}{ds} = -\hat{F}.\frac{d\hat{r}}{ds} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.13)$$

$$\left[\left|\frac{d\hat{r}}{ds}\right| = 1 \; ; \; (d\hat{r}/ds)^2 = 1 \; ; \; \frac{d(d\hat{r}/ds)^2}{ds} = 0 \; ; \; \frac{d^2\hat{r}}{ds^2} . \frac{d\hat{r}}{ds} = 0; \right]$$

Substituting equation (4.13) in equation (4.12) :

$$t\frac{d^2 r}{ds^2} = -\left[\hat{F} - \left(\hat{F}.\frac{d\hat{r}}{ds}\right)\frac{d\hat{r}}{ds}\right] \quad \ldots\ldots\ldots\ldots(4.14)$$

The R.H.S. of equation 4.13 and 4.14 is the tangential drag force (D_f) and the normal drag force (D_p) respectively. Replacing the R.H.S of these equation with the expression for the tangential force and the normal force with the assumption that the tangential force is zero the equations can be written as :

$$\frac{dt}{ds} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.14)$$

$$t\frac{d^2 r}{ds^2} = Fo\left[(Ux, Uy, Uz) - (l.Ux + m.Uy + n.Uz)(l, m, n)\right]$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.15)$$

Equation 4.15 can be separated into its component form as :

$$\frac{dl}{ds} = \frac{F_o}{t}\left[Ux\,(1 - l^2) - l.m.Uy - l.n.Uz \right] \quad \ldots\ldots\ldots(4.16)$$

$$\frac{dm}{ds} = \frac{F_o}{t}\left[Uy\,(1 - m^2) - l.m.Ux - m.n.Uz \right] \quad \ldots\ldots\ldots(4.17)$$

$$\frac{dn}{ds} = \frac{F_o}{t}\left[Ux\,(1 - n^2) - l.n.Ux - m.n.Uz \right] \quad \ldots\ldots\ldots(4.18)$$

To solve these equations we need three boundary conditions and the tension t in the cable. Since the only conditions known are the position coordinates of the two end points of the cable, the equations should be written in x,y,z coordinates instead of being for the direction cosines. These equations can be obtained by making the following substitutions :

$$\frac{dx}{ds} = l \; ; \qquad \frac{dy}{ds} = m \; ; \qquad \frac{dz}{ds} = n \; ;$$

Thus we have a system of six coupled single order ordinary differential equations which can be solved by Runge - Kutta scheme using the boundary conditions :

At $s = 0$; $x = 0$, $y = 0$, $z = 0$ (At vehicle end)

$s = L$; $x = X$, $y = Y$, $z = Z$ (At pulley end)

Since the tension t and the length L of the cable are unknown quantities the equations were solved following the procedure given below :

a] Assume the total tension in the cable .

b] Assume components of tension tcx,tcy,tcz in the x,y,z direction respectively at the vehicle end of the cable (0,0,0) . Using these l,m,n can be obtained .

c] The equations 4.16 to 4.18 can then be solved using the Runge Kutta scheme. The scheme is terminated at a point where the z co-ordinate at s = 1 is the required Z coordinate of the cable drum/pulley.

d] At s = 1 the x and the y coordinates of the cable should be the required position coordinate (X,Y,Z) of the pulley.

e] The procedure is repeated from steps b to d till the desired coordinates of the pulley are obtained.

Hence the only assumption made is the total tension in the cable, while all the other quantities are decided by the iterative procedure. The equations can be solved for different positions of the vehicle for different values of total tension giving the shape the cable will take and the magnitude of the three forces tcx,tcy,and tcz which will act on the vehicle.

CHAPTER V

GUIDELINES FOR SELECTION OF PROPULSION SYSTEM

5.1 Introduction

The propulsion system is the most important system of the designed submersible. This chapter provides the reasons for selection of screw propellers as a propulsive device. The comparison of vehicle power requirement depending on the propeller configuration is given in the next section. The procedure followed to select the propeller and the relationships to be used have been identified. The method to verify the selection of the propeller is also provided at the end of this chapter.

5.2 Propulsors

A simple example of a propulsive system can be seen when a body rises or falls in a fluid owing to the inequality of weight and buoyancy . However for horizontal motion where gravitational forces do not take any direct part it is necessary to attach some form of propulsor supplied with energy from a prime mover. The propulsor is that part of the system which is in

contact with the fluid and exerts a force on it in a way, such that the reaction force urges the vehicle to move forward. The chief difference between marine animals and the vehicle lies in the non - rigidity of the body of animals. Nature infers that there is no unique method of propulsion and so it is perhaps not surprising that in technology numerous propulsors exist. These are summarized briefly in order to aid in the selection of the system.

5.2.1 A Review of Propulsors

The oldest man made propulsors are the paddle or oar and wind generated thrust. Jet propulsion is the third type of propulsion system dating as far back as 1661[4] . The jet engine operates by transferring energy to the fluid entering the engine so as to increase the momentum flux of the fluid. The reaction to the increase of momentum flux provides the propulsive thrust exerted on the engine giving rise to motion.

The screw propeller was first used on a large ship by Brunel for the Great Britain in 1845 and has since remained most common method for ship propulsion. The present day screw propeller consists of 2- 20 but generally 3-7 blades of hydrofoil section mounted symmetrically on a boss fixed to a shaft. Relative motion between the blades and the fluid results from forward motion of the vehicle and the rotation of the propeller. As the surface of each blade lies on a helicoid generated about the shaft axis, this combined motion can be likened to that of a screw. The propeller shaft passes through glands and seals into the hull before being connected to the prime mover which may be steam or nuclear power plant ,diesel engine or electric motors.

In many cases the screw propeller is surrounded by a duct. There are two principal variants of the ducted propellers ; the pump jet and the kurt nozzle. The pump jet consists of a rotating impeller with fixed guide vanes (stator) and the whole unit is enclosed in a short duct concentric with the impeller. The kurt nozzle on the other hand has a axisymmetric duct with a hydrofoil section in the longitudinal direction.

5.2.2 Selection of Propulsor

To achieve steady motion of a marine vehicle over a range of speeds the propulsor should be capable of providing a net forward, steady, continuous thrust which can be easily varied in magnitude and direction. The paddle wheel,though a efficient means for propulsion requires very low speed engines, has large weight and is susceptible to damage. The hydraulic jet has a very low efficiency at low vehicle speeds[4]. The screw propeller is simple, reliable and a efficient means for propulsion. About 60 - 65 % power available at the shaft can be converted by the propeller for useful propulsion purposes. Thrust produced by screw propeller is continuous, steady, reversible and easily controllable by adjustment of shaft angular speed or the angular setting of the blade. The pump jet and kurt nozzle are expensive and difficult to install. Though thrust producing capacity in forward direction is higher by 40 % compared to that of a similar screw propeller the astern thrust producing capacity is undermined[4]. The screw propeller is the common choice as a propulsive device for the submersible .

5.3 Selection of Propeller Configuration

To have position control in a single degree of freedom, it must be possible to develop either a force or a couple of controllable direction and magnitude in a single plane. The submersible should have three degrees of freedom to reach a point in space.

The three degrees of freedom can be achieved by using one propeller , the axis of which can be rotated to give motion along the three directions or by using two propellers;one fixed to provide thrust for heave and the other propeller whose axis can be rotated in the horizontal plane to provide the thrust for surge and sidle. The third combination is that of three propellers with axis which cannot be rotated, providing the three degree of freedoms.

To rotate the axis of propeller the entire motor-propeller assembly has to be rotated. This will increase the sealing problems for the motor[7]. The electric connections from the fixed hull to the motor have to pass through slip ring assemblies. Since reliability of the system is important a simple arrangement is required with minimum of components, the 3 degree of freedoms are provided by using 3 propellers with fixed axis.

The three propellers can be placed in 3 different positions as shown in 5.1. In Fig 5.1 [a] the propellers are placed along each axis.They produce forces for surge, sidle and heave. Fig 5.1 [b] shows two propellers (P_1 and P_2) placed in the horizontal plane at 45° providing surge and sidle motion while the third

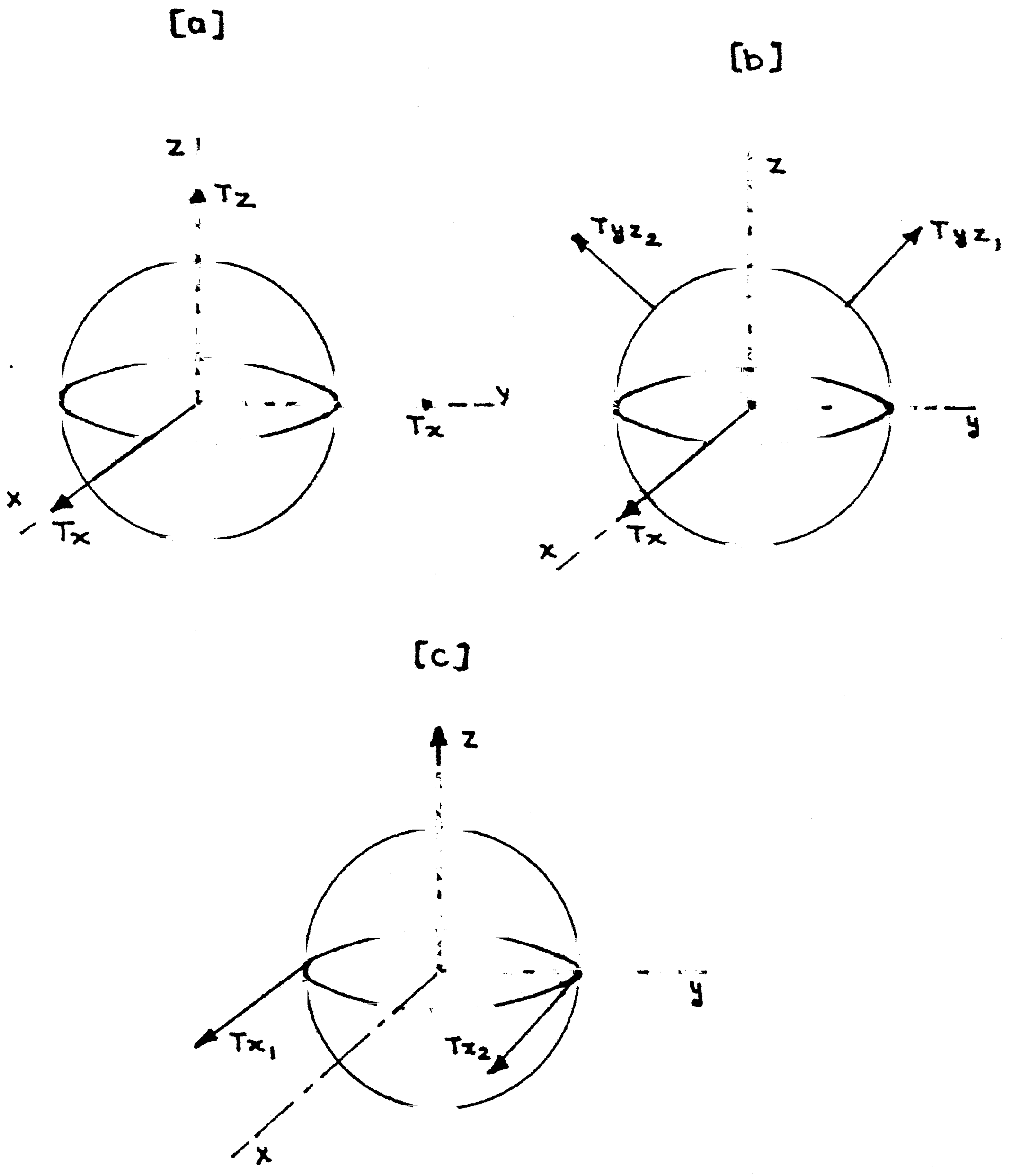


FIG 5.1 PROPELLER CONFIGURATION

propeller (P_3), fixed along the Z - axis provides heave. In the third case as shown in Fig 5.1 [c] the two propellers are placed in the horizontal plane, one each at the port and starboard side providing surge and yaw motion while the third propeller (P_3) provides heave force.

Consider the power requirement in each of the three cases described above. For producing a thrust of 100 N at a velocity of 1 m /sec the shaft horsepower is in the range of 250 W assuming a propeller efficiency of 0.4 . The total power requirement for each configuration is 750 W , 600 W and 500 W respectively.

The vehicle with a propeller configuration shown in Fig. 5.1 [c],has better maneuverability since any change in direction of vehicle can be corrected by the two horizontal propellers. This consideration favours the choice of configuration 3 shown in Fig. 5.1 [c] for the submersible.

5.4 Selection of Propeller Parameters

The propeller selection is usually based on established series using data from water tunnel tests. A detailed design of the propeller requires an analysis of hydrofoil section performance followed by optimum stacking of sections to form the blade geometry. The present work is limited to finding the optimum propeller diameter, efficiency, advance coefficient and the pitch to diameter ratio along with the speed and power ratings for the motor.

5.4.1 Glossary of Terms

Before proceeding it is necessary to define certain commonly used terms related to propeller selection [1] :

a] Developed Blade Area (A_d) :

It is the sum of the face area of all the blades.

b] Projected Blade Area (A_p) :

It is the projected area of the blades on to a plane normal to the propeller axis .

c] Disc Area (A_o) :

It is the area of the circle passing through the tips of the blades and normal to the propeller axis.

d] Blade Area ratio (BAR)

It is the ratio of the developed blade area to the disc area

e] Expanded Blade Area (EBR)

If the variation of helical chord length with the radius is known the true blade area can be obtained analytically by integration. This area is called the expanded blade area .

f] Expanded Area Ratio (EAR)

The ratio of expanded blade area to the disc area is called the expanded area ratio.

g] Pitch (p) :

A helicoidal surface is generated by a line rotated about an axis normal to itself and advancing in the direction of the axis at constant speed. The distance the line advances in one complete revolution is termed as the pitch

h] Analysis Pitch :

The distance advanced by a propeller during one

revolution when delivering no thrust is termed as analysis pitch.

i] Face Pitch Ratio :

This is the ratio of the face pitch of the propeller and diameter.

j] Slip

When developing thrust the propeller advance/rev is less than the analysis pitch. The difference is termed as slip.

h] Slip ratio :

It is the ratio of slip to the analysis pitch.

5.4.2 Notation

V : Velocity of vehicle m/sec

D : Diameter of propeller m

n : angular speed rps

N : angular speed rpm

ρ : density of fluid kg/m^3

μ : dynamic viscosity

p : propeller pitch m

η : efficiency %

α : pitch ratio

B_p : Taylor's basic coefficient

K_t : Thrust Coefficient

K_q : Torque Coefficient

J : Advance Coefficient

R_e : Reynold's Number

S_n : Nominal Cavitation Number

T : Thrust N

Q : Torque Nm

P : Shaft power W

$\hat{P} - P_v$: Pressure of fluid relative to vapour pressure.

5.4.3 Open water Tests

The behavior of the propeller is vital to the performance of the vehicle. Consequently, the design and assessment of a marine propeller when attached to the vehicle must be substantiated by model tests.

Suppose that a propeller is deeply immersed in a uniform, homogeneous, steady, constant density flow approaching the propeller in a direction parallel to its axis of rotation. The thrust developed and the torque absorbed may be considered to depend on the axial velocity ,diameter, angular speed , density, viscosity and the pressure of fluid relative to the vapour pressure.

The application of dimensional analysis[4] to the preceding parameters show that :

$K_t = f(J, Re , Sn)$

$k_q = f(J, Re , Sn)$

where

$$K_t = \frac{T}{\rho . n^2 . D^4} \quad \text{.....................................} (5.1)$$

$$K_q = \frac{Q}{\rho . n^2 . D^5} \quad \text{.....................................} (5.2)$$

$$J = \frac{V}{n \cdot D} \quad \text{...(5.3)}$$

$$R_e = \frac{\rho \cdot D \cdot V}{\mu} \quad \text{...(5.4)}$$

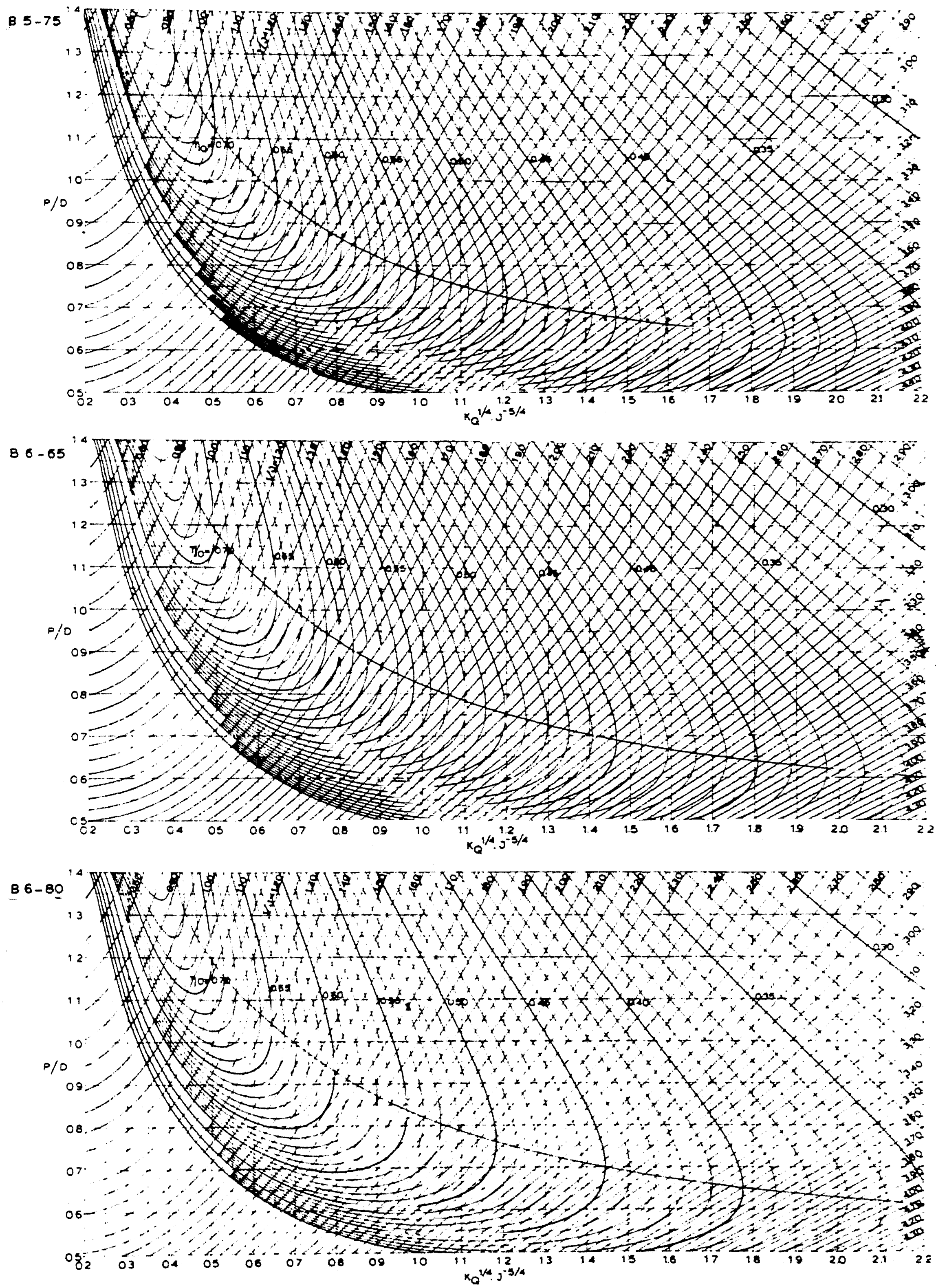
$$S_n = \frac{\hat{p} - p_v}{0.5 \cdot \rho \cdot V^2} \quad \text{.................................(5.5)}$$

Propeller designs are based on established series using data from water tunnel tests and propeller theories. The results are generally presented in the form of Taylor's charts. The charts illustrate the relationship between open water efficiency , advance coefficient , pitch to diameter ratio, and the delivered power for propellers with different number of blades. A screw series is formed by a number of screw models of which only the pitch ratio is varied .Taylor's charts for a Wagenin B - series propellers for a four bladed propeller is shown in Fig 5.2

5.4.4 Procedure for Propeller Selection

To investigate a series of propellers suitable for the submersible read for different valuesof B_p , the corresponding values of J, α and η from Taylor's charts. Using these values for a known value of power and velocity the speed diameter and pitch of the propeller can be computed using following relationships[13] :

$$n = \frac{V^{2.5} \cdot B_p}{P^{0.5} \cdot 0.408} \quad \text{..........................(5.6)}$$



F IG. 5.2 TAYLOR'S CHARTS

$$D = \frac{V}{J \cdot n} \qquad \text{.........................(5.7)}$$

$$P = \alpha \cdot D \qquad \text{.........................(5.8)}$$

To calculate the torque required and the thrust produced the torque coefficient and thrust coefficient should be known. These can be calculated by using the following relationships[40]:

$$K_q = \frac{B_p^2}{33.08^2} \qquad \text{.................................(5.9)}$$

$$K_t = \frac{2 \cdot \pi \cdot K_q \cdot \eta}{J} \qquad \text{.........................(5.10)}$$

With the coefficients calculated along with the diameter and speed at which the propeller runs the thrust produced and the torque can be calculated using equations 5.1 and 5.2 .

Hence for different values of B_p and shaft power the propeller diameter ,speed, pitch, thrust and torque can be calculated using the equation 5.3 to 5.10. Graphs of speed, thrust and efficiency versus the required propeller diameter can be drawn for different values of shaft power.

A set of graphs to aid the selection of the propeller are shown in Fig 5.3 to 5.5. Fig 5.3 is a graph of propeller diameter vs the thrust requirement. The thrust obtained from a propeller increases if the diameter of the propeller is higher for the same shaft power . Higher the shaft power lower is the diameter of the

propeller required to provide the same thrust. From Fig 5.4 it can be seen that it is more efficient to use a propeller with a bigger diameter. Fig 5.5 shows that lower the size of a propeller, higher is the speed, eliminating the need of gear reduction. The torque requirement is also low resulting in a lighter propulsion system.

For a submersible, size and weight are two important considerations. The diameter of a propeller will play a stellar role in deciding the overall dimensions of the vehicle, therfore it should be kept to a minimum. A propeller of bigger diameter runs at a lower speed, requiring means for speed reduction adding weight to the the system. This undermines the advantage gained by using a low powered motor than that required to run a smaller propeller.

5.4.5 Procedure for Verification of Selected Propeller :

The propeller is selected on the basis of maximum velocity V and supplied power. Since the vehicle may move at speeds (v) lower than the maximum it is necessary to check if the propeller can provide the required thrust at that speed(v). The following steps describe the method followed for the verification. The actual calcuations are given in section 6.3.1.2.

a] Select B_p for the propeller from Taylor's chart.

b] The propeller selection procedure gives the pitch ratio of the propeller. At this value of α read values of η and J for the choosen value of B_p.

c] Calculate K_t and K_q using equations 5.9 and 5.10.

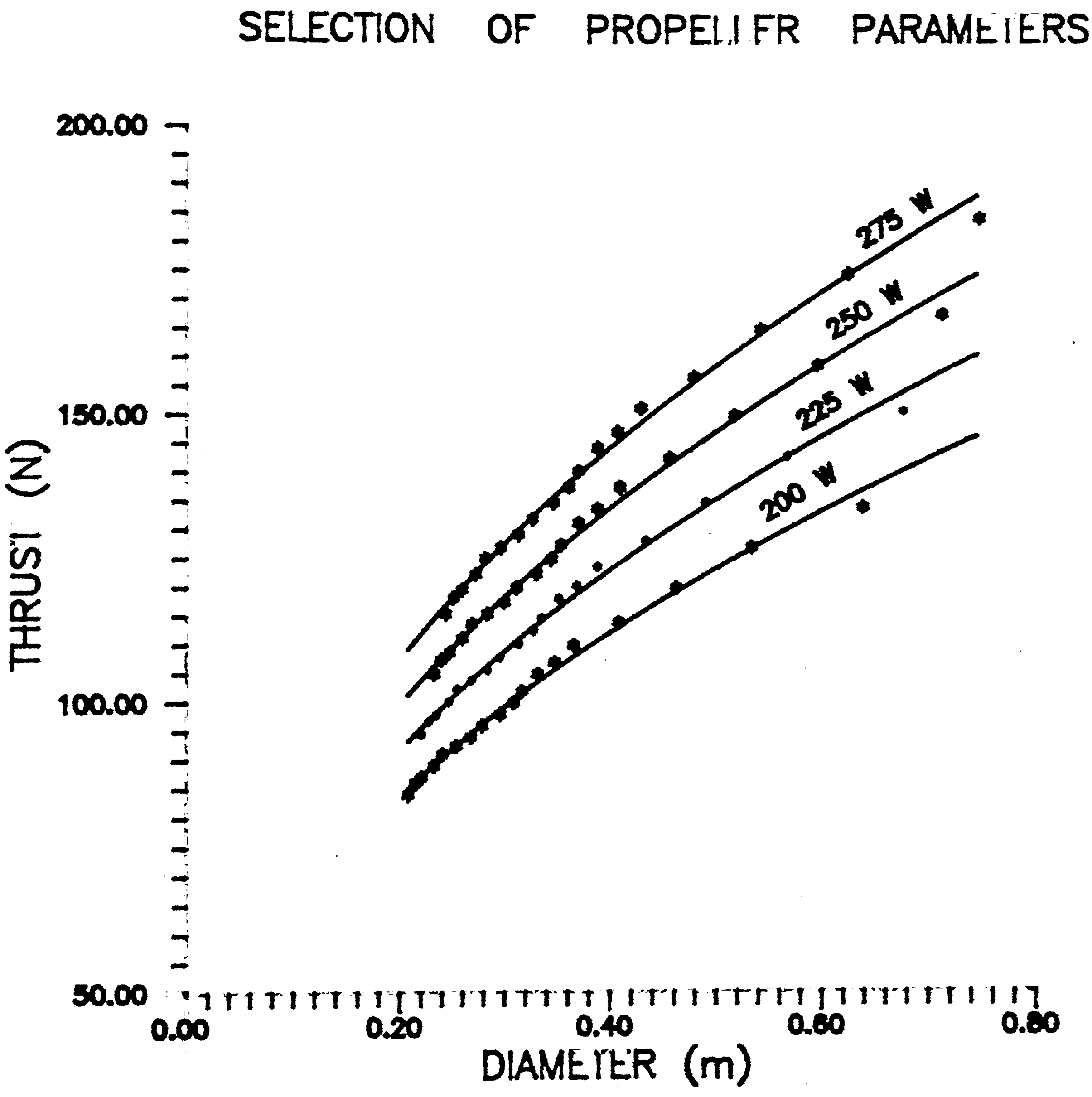


Fig. 5.3 : Graph of Propeller diameter vs thrust for various values of input power.

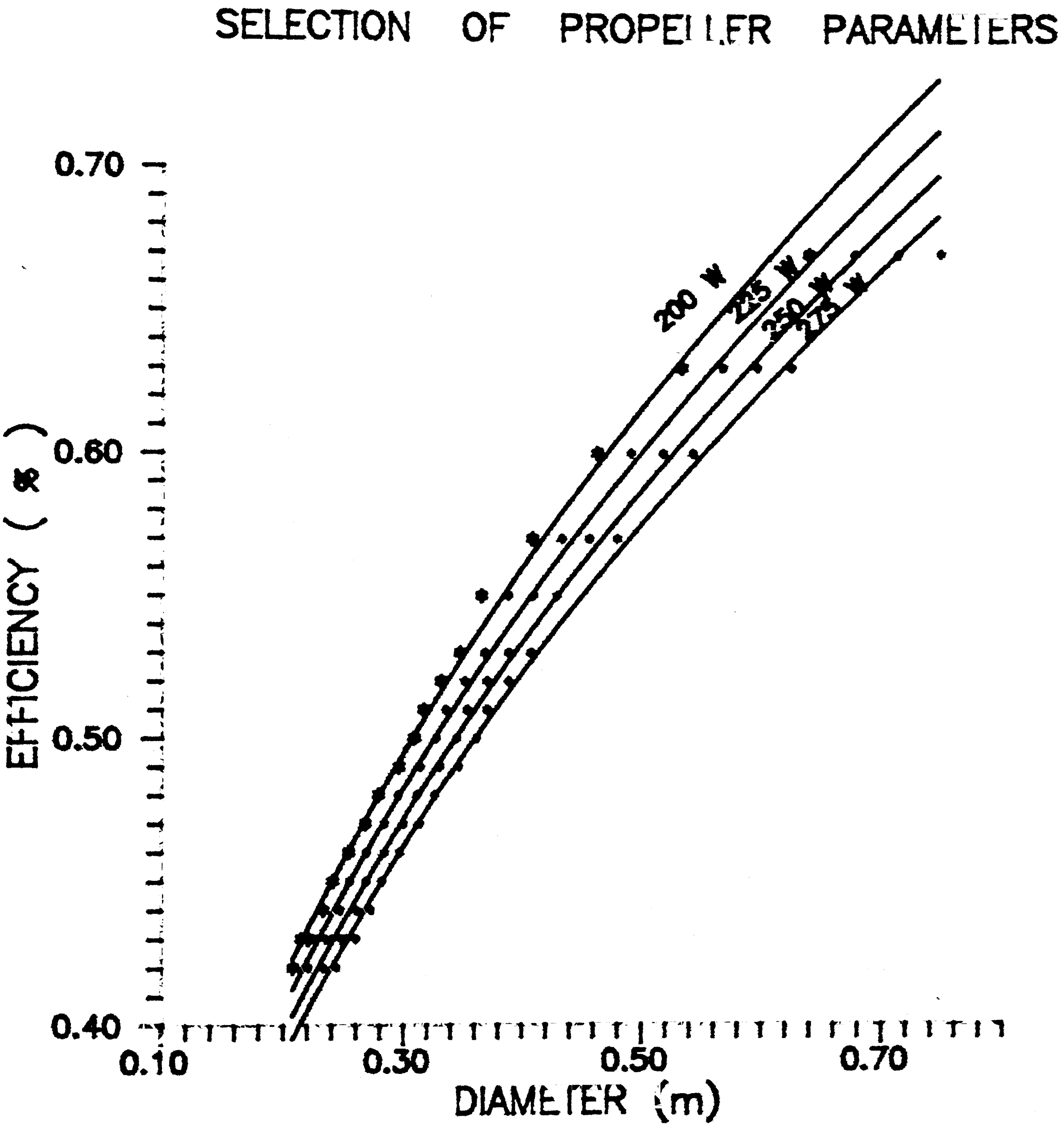


Fig. 5.4 : Graph of propeller diameter vs overall efficiency for various values of input power.

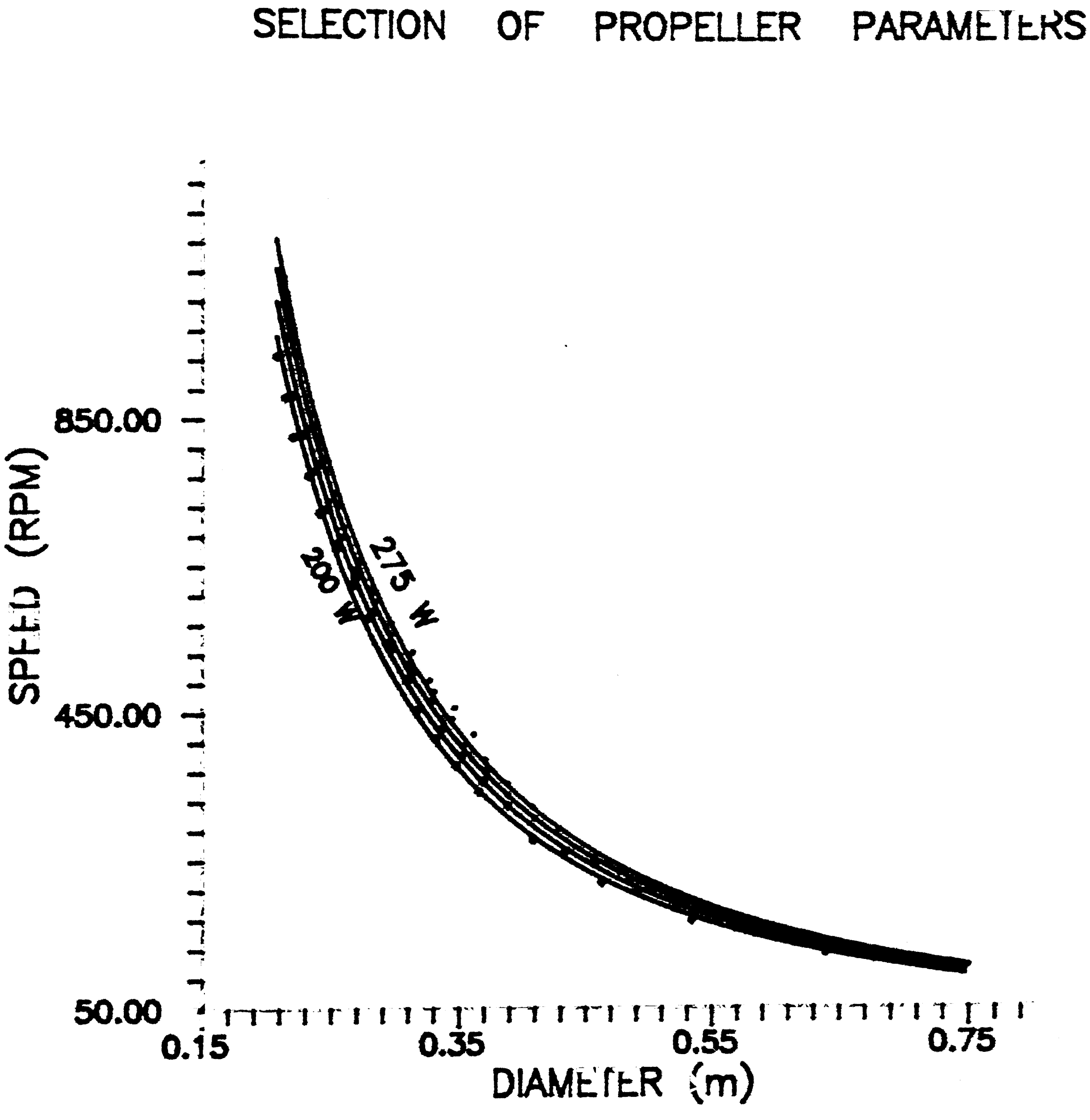


Fig. 5.5 : Graph of propeller diameter vs propeller speed for various values of input power.

d] Calculate angular speed n using equation 5.6 .

e] Calculate thrust using equation 5.1.

f] Check if the thrust produced is the required thrust for propelling the vehicle at velocity v. If it is not then select another combination of B_p ,η and J , till the value of B_p satisfying the above requirement is arrived at.

f] Calculate the power required using equation 5.6.

g] Check if this is higher than the power supplied by the motor. It should be less than the power supplied by the motor. (A higher power is required only if the velocity of the vehicle is higher than that for which it was selected.

CHAPTER VI

FORCE CALCULATIONS

6.1 Introduction

This chapter deals with the calculations of the hydrostatic forces, drag forces and the cable forces acting on the vehicle as seen in chapter - 3. The relationships established in chapter- 4 are used for the force estimation.

6.2 Drag Force Estimation

The forces acting on the vehicle have been identified in Chapter-3 and the expressions or the methodology to calculate the forces has been established in Chapter -4. This section deals with the calculation of the hydrostatic forces and drag forces acting on the submersible, assuming steady state motion.

6.2.1 Hydrostatic Force Calculations

The hydrostatic forces acting on the vehicle are the weight and the buoyant forces. The weight and the buoyant volume of the vehicle components is given in a tabular form in the

ASSEMBLY	COMPONENT	MATERIAL VOLUME m^3	DENSITY kg/m^3	VOLUME DISPLACED m^3	WEIGHT N	BUOYANT FORCE N
Hull	Tank	0.0241	2600	0.146	615.5	1432.3
	FrontCover	0.0052	1600		81.6	
	Back Cover	0.0055	1600		86.3	
Motor Assembly 1 & 2	Motor	-	-	2.0 * 0.17	412	333
	MotorCover	0.0024	2600		122.5	
	ShaftCover	0.00056	2600		28.5	
Motor Assembly 3	Motor	-	-	0.001	206	9.81
	ShaftCover	0.00056	2600		14	
Pan & Tilt Mech-anism	Camera	-	-		6.9	-
	Motors	-	-		40	-
	Platform	0.0008	2600	-	21	-
	Rev Base	0.00045	2600		12	
	Base	0.0007	2600		18	
Detector		-	-	-	2.5	-
Lights		-	-	-	5	-
Panel Board		0.0008	-	-	20	-
Coupling		0.0004	-	-	10	-
Dead Weight		0.0028			73	-
	Total				1775	1775

Table 6.1 Weight and Buoyancy Calculations.

Table - 6.1. The weight of the vehicle with its components is equal to 1702 N while the buoyant force is 1775 N. The difference is taken care of by attaching a dead weight of 73 N for making the vehicle neutrally buoyant.

6.2.2 Drag Force Calculations

The expression for calculating the vehicle drag force is given in Section - 4.3 as :

$$D = 0.5 * \rho * C_d * A * V^2 \quad \ldots\ldots\ldots\ldots\ldots (6.1)$$

The values of density and the drag coefficients are taken as follows :

ρ = 1000 Kg/m^3

C_d = 1.0 , for a flat surface.

Cd = 0.25 for a cylindrical or spherical body .

The projected area for the vehicle in x direction motion consists of three parts; the area of the front cover (Ac),the area of the two motor covers (Amc) and the area of the propeller shaft cover (As). The area for vertical motion consists of the area of the hull (Ah),and the motor assembly (Ama). The calculated areas are given below. The dimensions are taken from the Table - 6.2

$$Ac = b * h = 0.44 * 0.34 = 0.150 \ m^2$$

$$Amc = \frac{\pi * d^2}{4.0} = \frac{\pi * 0.3^2}{4.0} = 0.071 \ m^2$$

$$As = l * d = 0.2 * 0.08 = 0.016 \ m^2$$

$$Ah = l * b = 1.0 * 0.44 = 0.440 \ m^2$$

$$Amc_h = l * d + \frac{\pi * d^2}{4.0} = 0.42 * 0.3 + \frac{\pi * 0.3^2}{4.0} = 0.197 \ m^2$$

$$Ama = Amc_h + Amc + As = 0.197 + 0.071 + 0.016 = 0.142 \ m^2$$

Assembly	Component	Overall Dimensions
		l.b.h or ϕ . l
Hull	Tank	1.0 * 0.44 * 0.34
	FrontCover	0.2 * 0.44 * 0.34
	Back Cover	0.44 ϕ * 0.34
Motor Assembly 1 & 2	Motor	0.25 ϕ * 0.40
	MotorCover	0.3 ϕ * 0.42
	ShaftCover	0.08 ϕ * 0.192

Table 6.2 Overall Dimensions of Components Producing Drag

The drag force acting on the cable for speeds ranging from 0.2 m/sec to 1.0 m/sec is given in Fig 6.1 for horizontal and vertical motion . The drag force is a function of velocity square. For a velocity of 1 m/sec the drag force in the horizontal direction is 94.75 N while that in the vertical direction is 255.5 N

Sample Calculation :

The sample calculation is given for a axial velocity of 1 m/sec in the horizontal and vertical motion .

D_{x2} = Front Cover Drag + 2.0 * Motor Cover Drag

$= 0.5 * 1000 * [(1.0 * 0.15 * 1^2) + 2.0 * (0.25 * 0.071 * 1^2)$

$= 92.75$ N ..

D_{x2} = Shaft Cover Drag

$= 0.5 * 1000 * 0.25 * 0.016 * 1^2$

$= 2$ N

$D_x = D_{x1} + D_{x2}$

$= 94.75$ N

D_z = Hull Drag + 2.0 * (Motor Assembly Drag)

$= 0.5 * 1000 * [(1.0 * 0.44 * 1^2) + 2.0 * (0.25 * 0.142 * 1^2)$

$= 255.5$ N

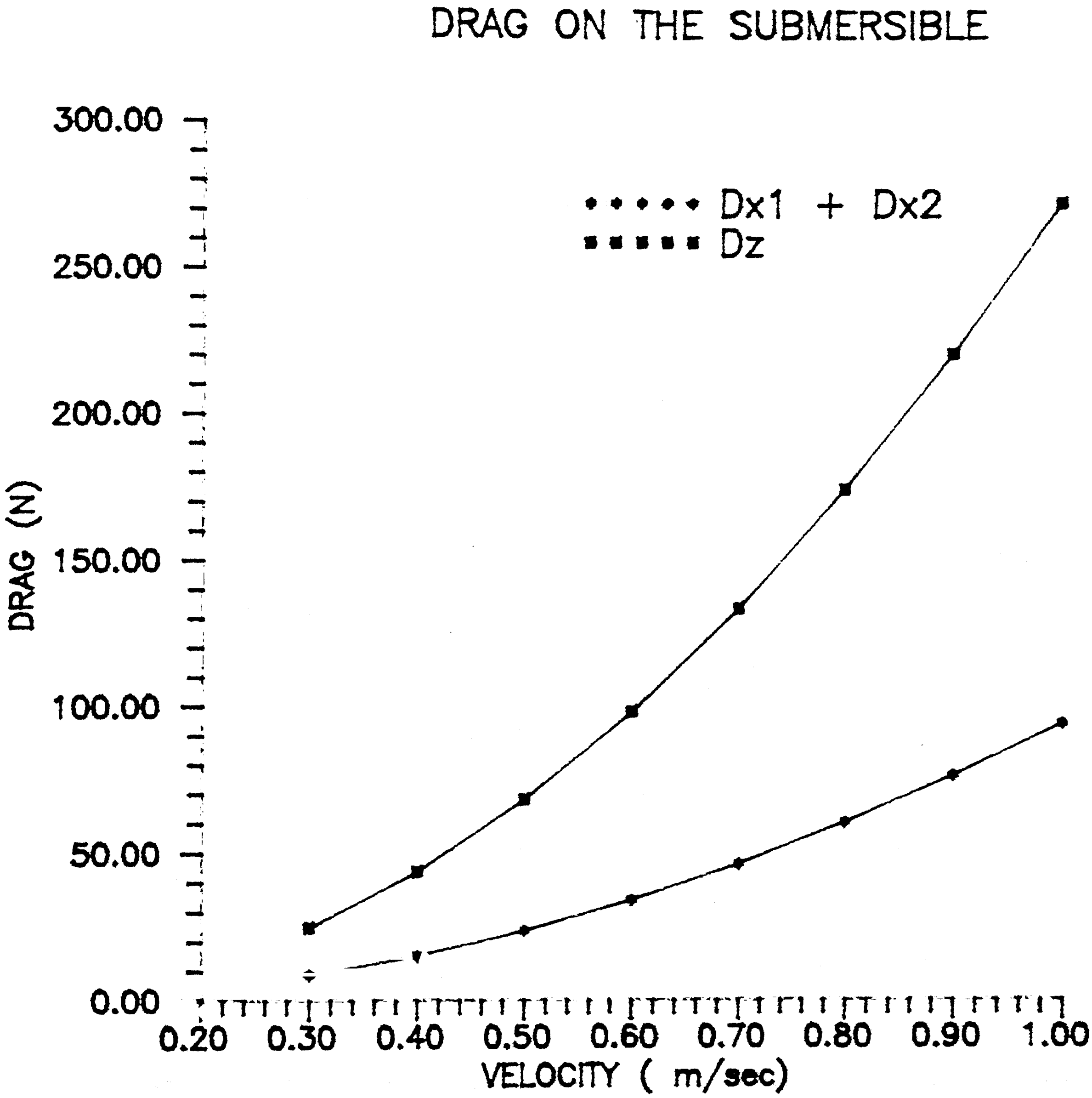


Fig. 6.1 Graph of axial velocity of vehicle vs the drag force.

6.3 Cable Force Calculations

The equations for finding the tension in the cable were established in Section - 4.4.1. To solve these equations it is necessary to know the velocity of the cable. The average velocity of the cable is assumed to be half the vehicle velocity since one end of the cable moves at vehicle velocity while other moves is pivoted on a pulley.

The profile taken by the cable will change if the total tension in the cable, for the same vehicle velocity (1 m/sec) is varied as shown by the Fig 6.2. A change in the position of the vehicle will alter the cable configuration and the force components. To study the shape taken by the cable and the forces it will exert on the vehicle, the equations were solved for several different positions of the vehicle. For solving the equations the vehicle coordinates were taken as (0, 0, 0) as explained in section 4.4.1 and the coordinates of the pulley end were (X, Y, Z). To draw the graphs such that the pulley end of the cable is same for any position of the vehicle, the axis was shifted so that the pulley end has coordinates (0,0,0) and the vehicle end has coordinates (-X, -Y, -Z). The total tension is kept constant at a value of 10 N. The following cases of vehicle moving in different directions were investigated :

a] Velocity only in the X direction, forward (ie. negative velocity) and reverse (ie. positive velocity).

b] Velocity only in the Z direction, Up (ie. positive velocity) and down (ie. negative velocity) .

c] Equal velocity in the X and Y direction, forward or reverse.

Table 6.3 . gives the component of the cable tension in the x,y,z direction at the vehicle end of the cable, for extreme positions of the vehicle in the tank. The respective cable profiles are depicted in Fig 6.3 to Fig 6.7 . The following observations can be drawn from the graphs and the table :

a] Fig 6.3 shows the profile taken by the cable when the vehicle moves with a negative velocity or away from the pulley. As the vehicle moves further the tension in the X - direction increases, resulting in excess thrust requirement. The slack in the cable increases.

b] From Fig 6.4 it can be seen that as the submersible moves towards the pulley or with a positive velocity, the overhang or slack in the cable increases. At the extreme end, away from the pulley (X = -12 m ; Z = -12 ,m) the cable is practically vertical meaning the force in the X - direction is zero. As the vehicle moves towards the pulley, the force in the X - direction increases. If the tension in the cable is higher (25 N) the cable profile is such so as to actually assist the motion in the X - direction (refer to Fig. 6.3). At lesser depths (Z = - 4 m) the X - component of the cable tension is in the direction of motion.

c] Consider the graph shown in Fig 6.5 [a] for a vehicle moving in the positive Z - direction. As the depth of the vehicle increases the overhang in the cable decreases and the Z - component of the tension ie. the force opposing the motion, decreases in magnitude. If the tension in the cable was higher than 10 N (resulting in a relatively taut configuration), the direction of the Z - component force will be the same as the vehicle direction.

Fig 6.5 [b] shows the profile of the cable in the Y-Z plane. As the vehicle moves upwards the tension in the Y - direction decreases since the cable slack increases.

d] Fig 6.6 [a] and [b] show the cable configuration in the X-Z and Y-Z plane respectively, when the vehicle is moving in the downward direction. As the submersible moves deeper the force in the Z - direction increases resulting in higher thrust requirement. If the vehicle is away from the pulley end (X = -12; Z = -10) the cable is slack and the force in the Z direction is less than that to when the vehicle is closer to the pulley. In the Y-Z plane increase in the vehicle depth reduces the force in the Y - direction.

e] Fig 6.7 [a] and [b] represent the cable profiles in the X-Z plane and the Y-Z plane respectively for a vehicle moving with equal velocity in both X and Y direction or at 45° to the X or Y axis. As the vehicle moves towards or away from the pulley the direction of the forces in X or Y direction is to oppose the motion of the vehicle.

In conclusion of the above discussion the following points can be stated regarding the cable tension.

a] The force which the vehicle is subjected to will change in direction with change in position of the vehicle. The force in the direction of motion will vary from 0 - 9 N depending on the position of the vehicle.For any further calculations the maximum value of the cable force will be taken as 10 N in any direction.

b] When the cable moves away from the pulley or with a negative velocity, lesser the total tension in the cable the better it is, from the point of view of thrust required and the unbalanced

moments to which the vehicle will be subjected to . A lower tension in the cable means there is extra length of the cable in the pond which increases the chances of fouling.

c] A high tension in the cable is not so detrimental, in the case when cable moves towards the pulley since the direction of the cable force is along the vehicle direction. This means that the vehicle is being pulled by the motor driving the winch. The advantage is undermined by the fact that a high tension will subject the vehicle to moments which have to be balanced by the propellers . Since the propellers are capable of providing the required thrust the cable tension can be limited to 10 N .

TENSION			POSITION of VEHICLE			VELOCITY		
tcx	tcy	tcz	X	Y	Z	Vx	Vy	Vz
N	N	N	m	m	m	m/s	m/s	m/s
-7.8	-1.0	-6.0	-2	-2	-12			
-9.9	-0.6	-4.0	-12	-2	-12	-1.0	0	0
-6.5	-3.5	-7.0	-2	-2	-4			
-8.7	-1.0	-5.0	-12	-2	-4			
6.4	-1.2	-7	-2	-2	-12			
1.1	-1.2	-9.5	-12	-2	-12			
-1.0	-4.5	-9.0	-2	-2	-4	1	0	0
-8.8	-2	-4	-12	-2	-4			
-2.2	-4.4	-8.8	-2	-4	-12			
-9.5	-3.2	1	-12	-4	-12	0	0	1
-8.0	-2.7	4.03	-12	-4	-6			
-2.9	-5.7	-8.0	-2	-4	-4			
-5.2	-2	-9	-10	-4	-4	0	0	-1
-1.4	-2.8	-9	-2	-4	-10			
4.15	4.15	-8	-2	-2	-12	0.7	0.7	0
4.4	2.9	-9	-2	-4	-12			
-5.8	-5.8	-6.5	-2	-2	-12	-0.7	-0.7	0
-5.6	-6.6	-6	-2	-4	-12			

Table 6.3 Components of Cable Tension.

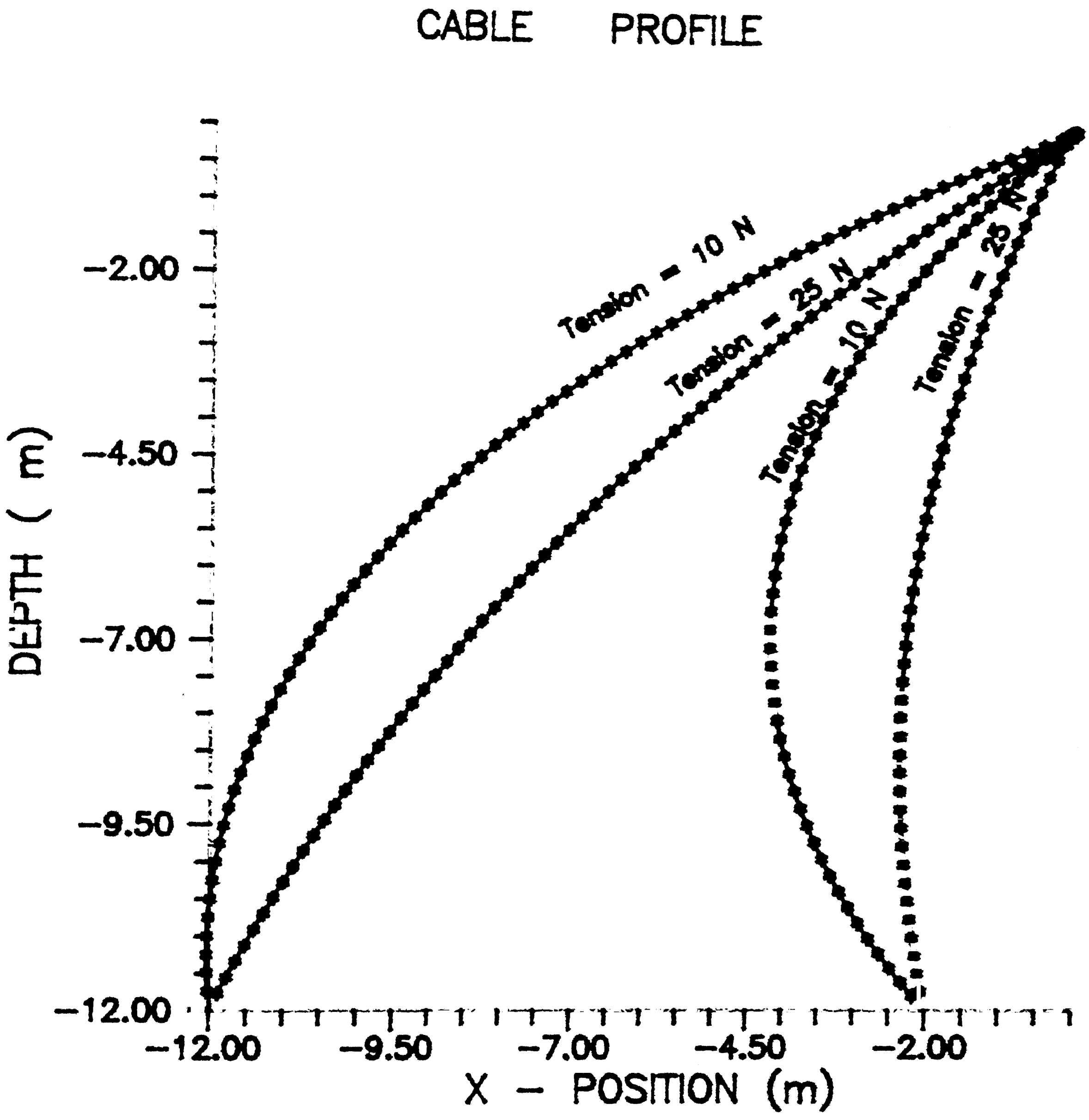


Fig. 6·2 : Cable profile in the X–Z plane. Effect of change in tension in the cable is studied.

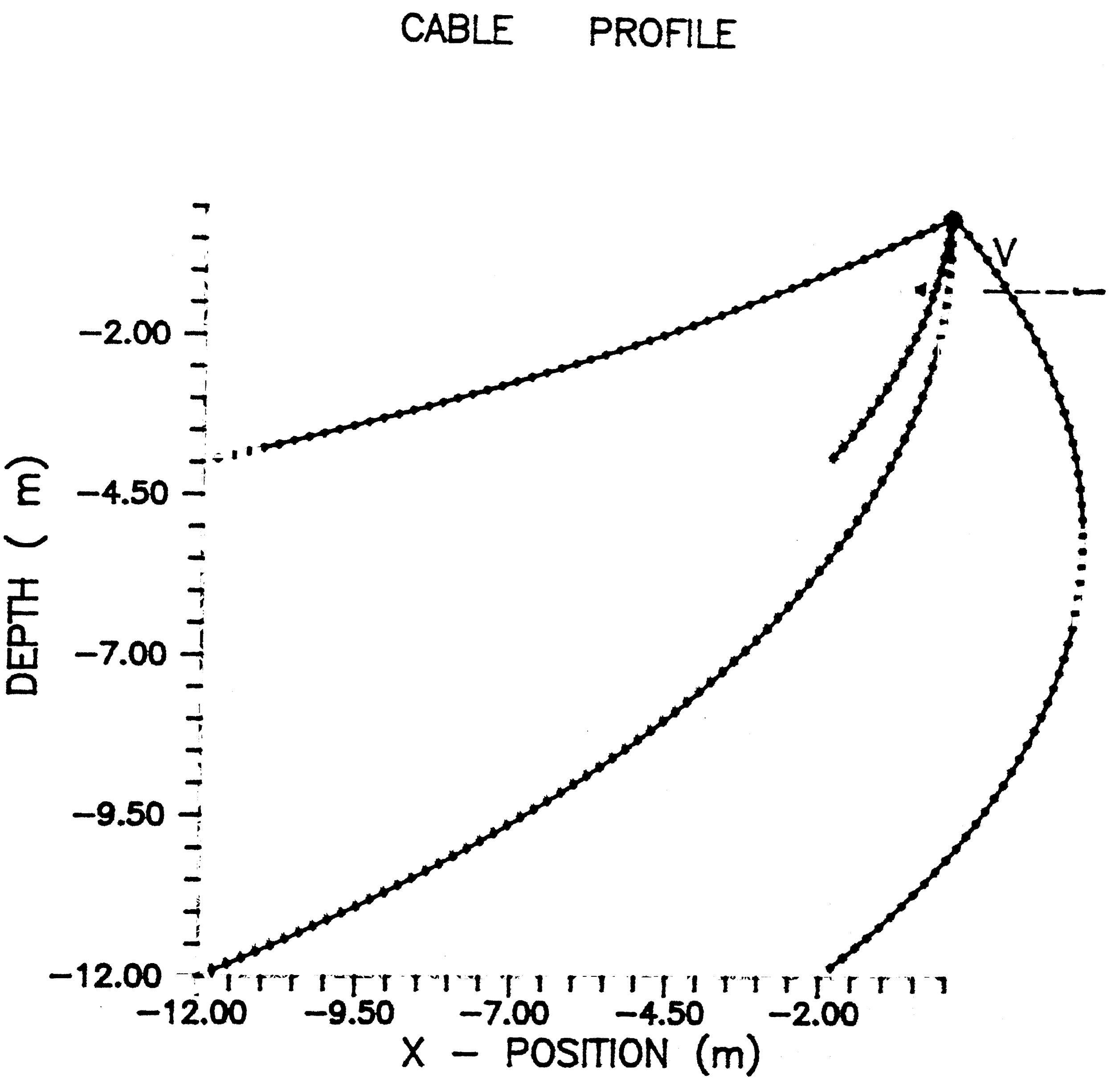


Fig. 6.3 : Cable profile in the X-Z plane for different positions of the submersible moving in negative X- direction.Total tension = 10 N

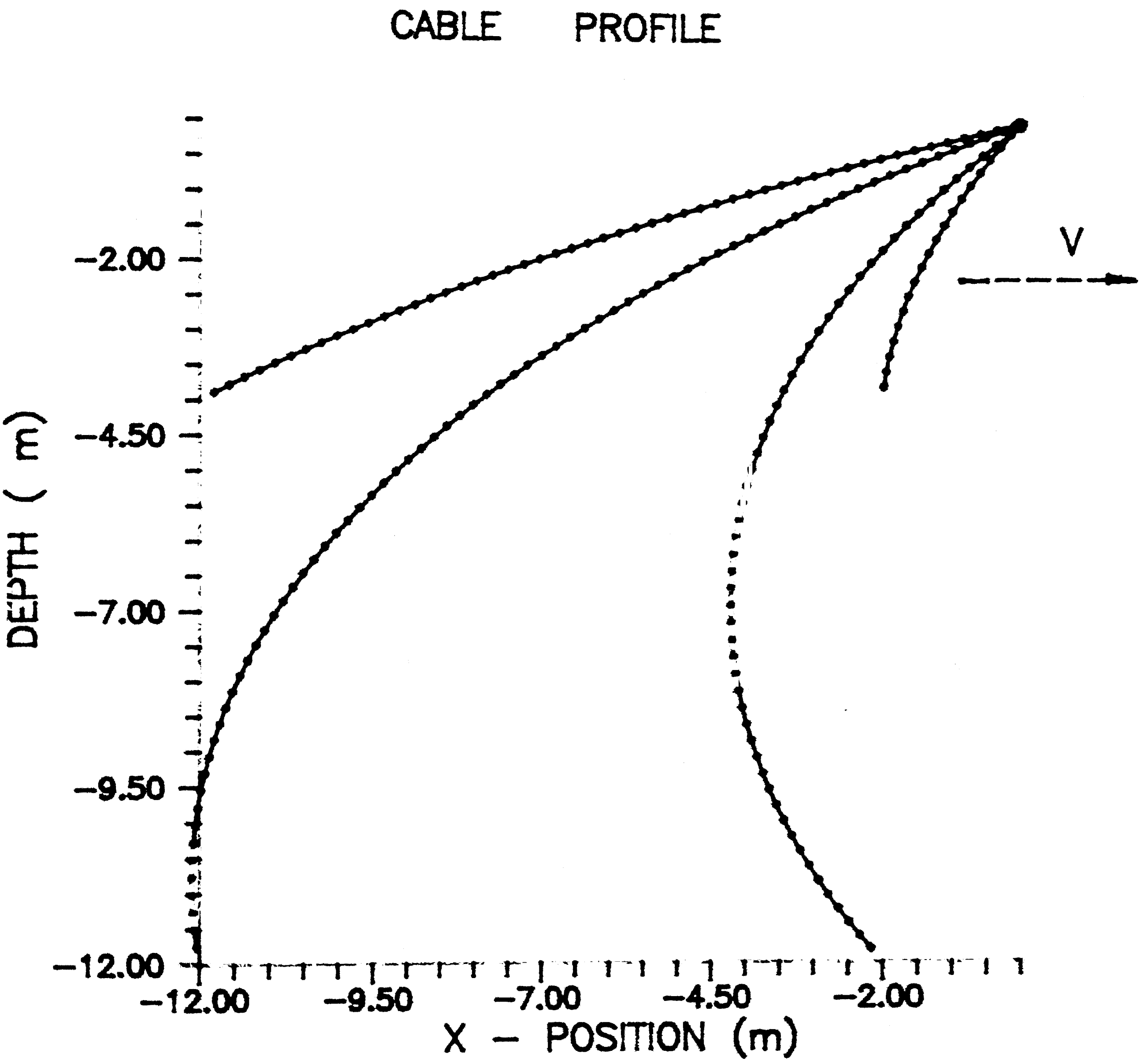


Fig. 6.4: Cable profile in the X-Z plane for differnt positions of the submersible moving in positive X direction.Total tension = 10 N

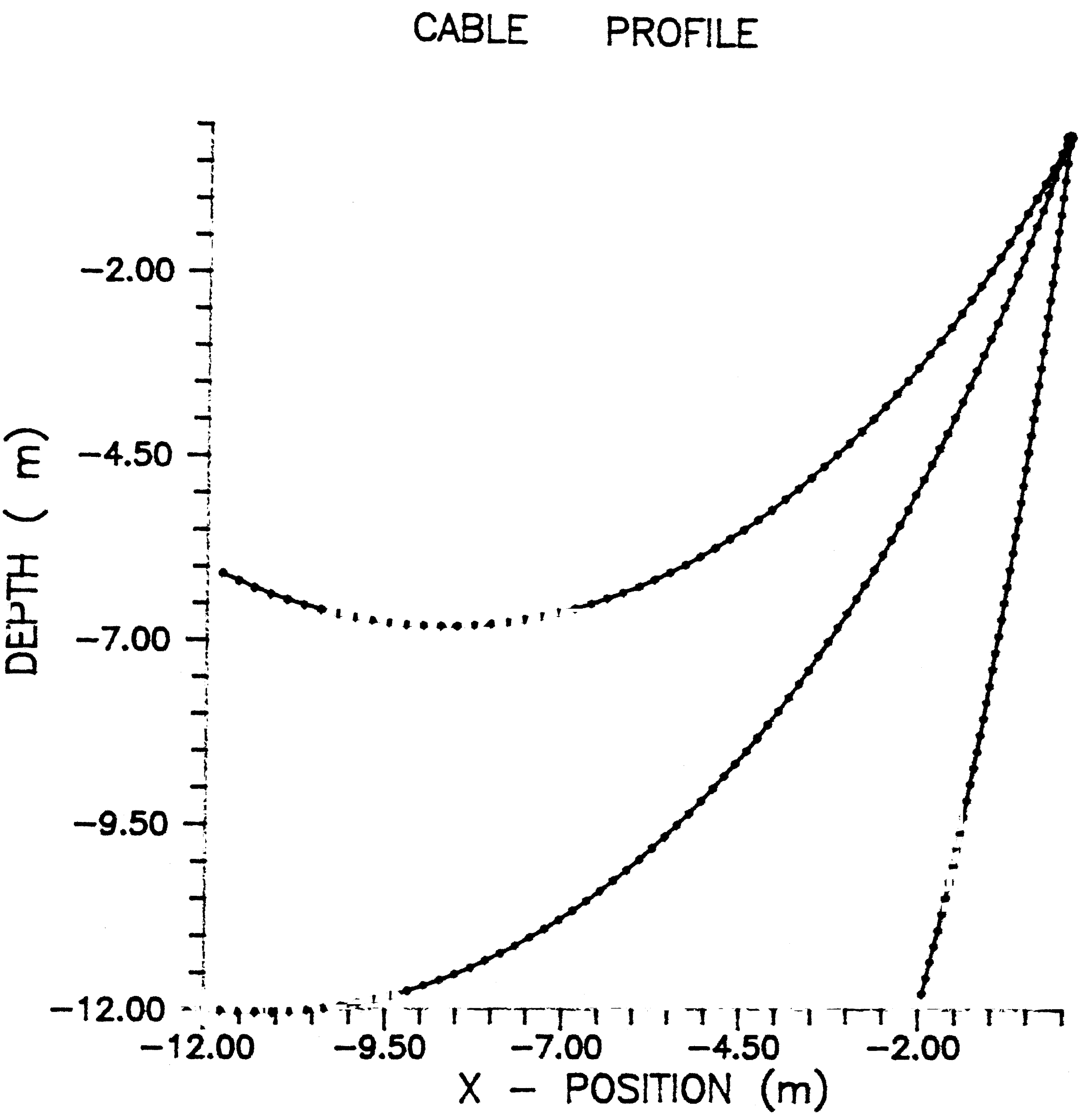


Fig. 6.5 a: Cable profile in the X–Z plane for different positions of the submersible moving in the positive z direction. Total tension = 10 N. Y–Position = –4 m.

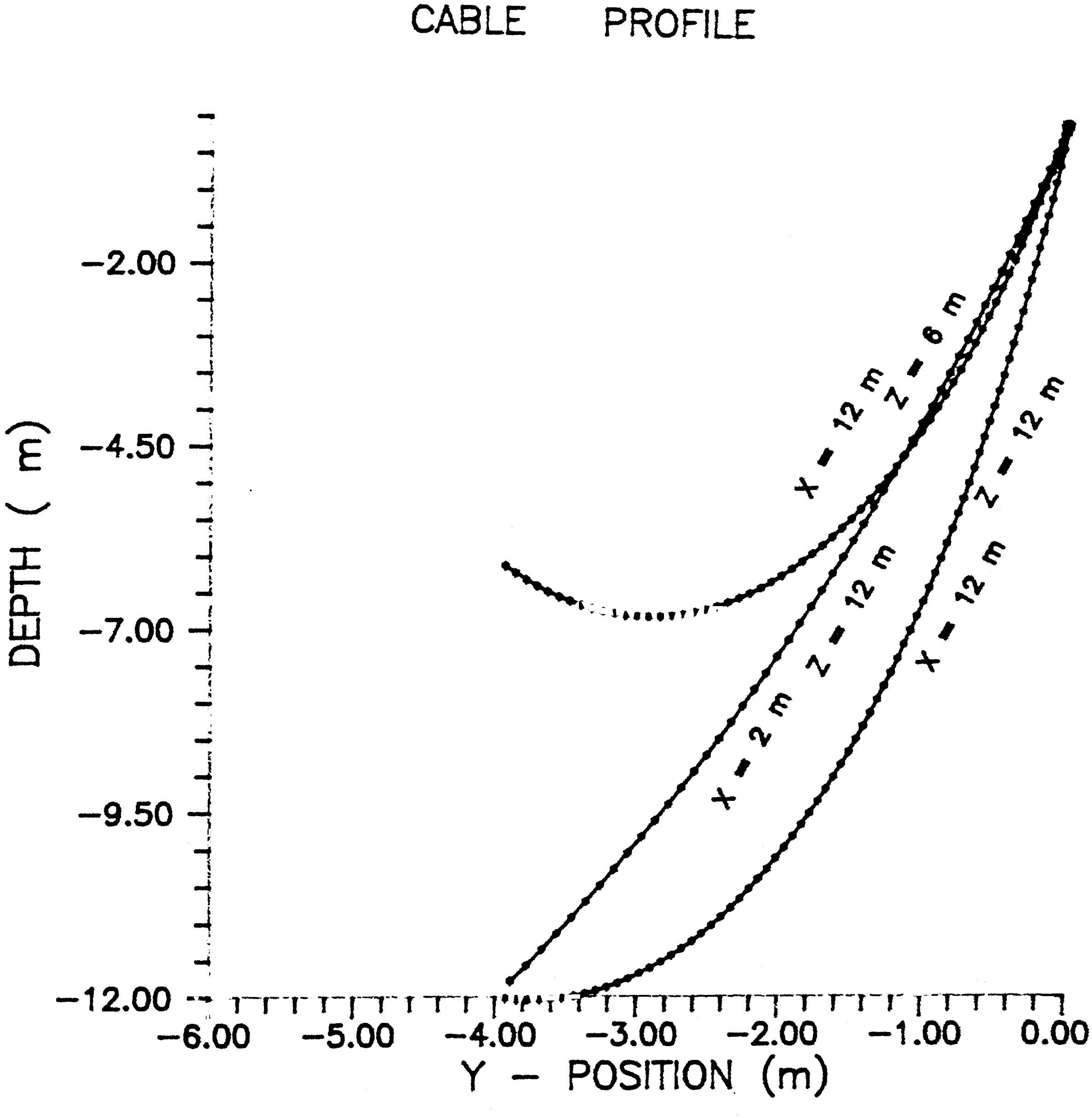


Fig. 6.5 b: Cable profile in the Y–Z plane for different X–positions of the submersible moving in the positive z direction.Total tension = 10 N.

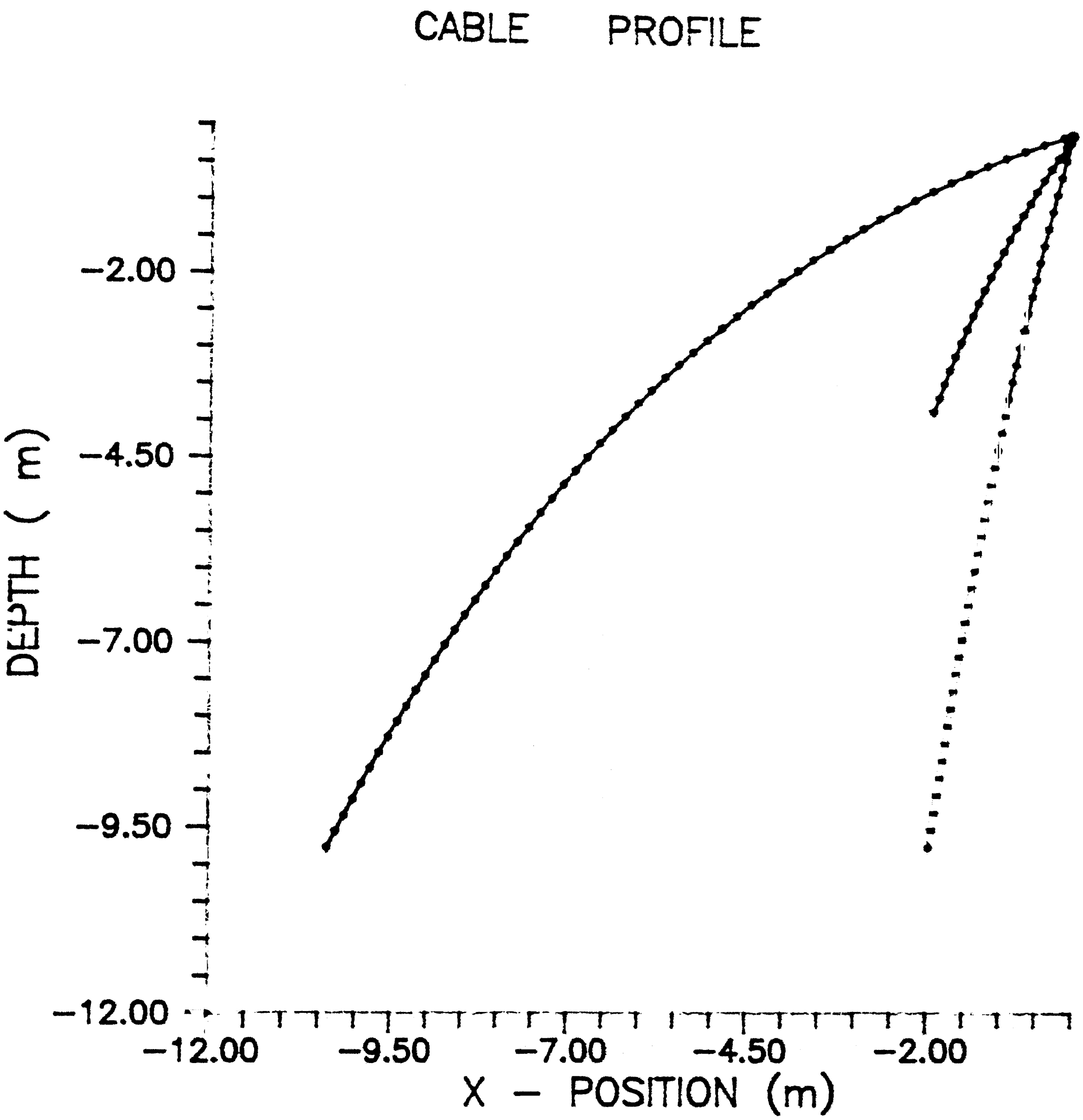


Fig. 6.6a: Cable profile in the X-Z plane for different positions of the submersible moving in the negative z direction. Total tension = 10 N. Y-Position = -4 m.

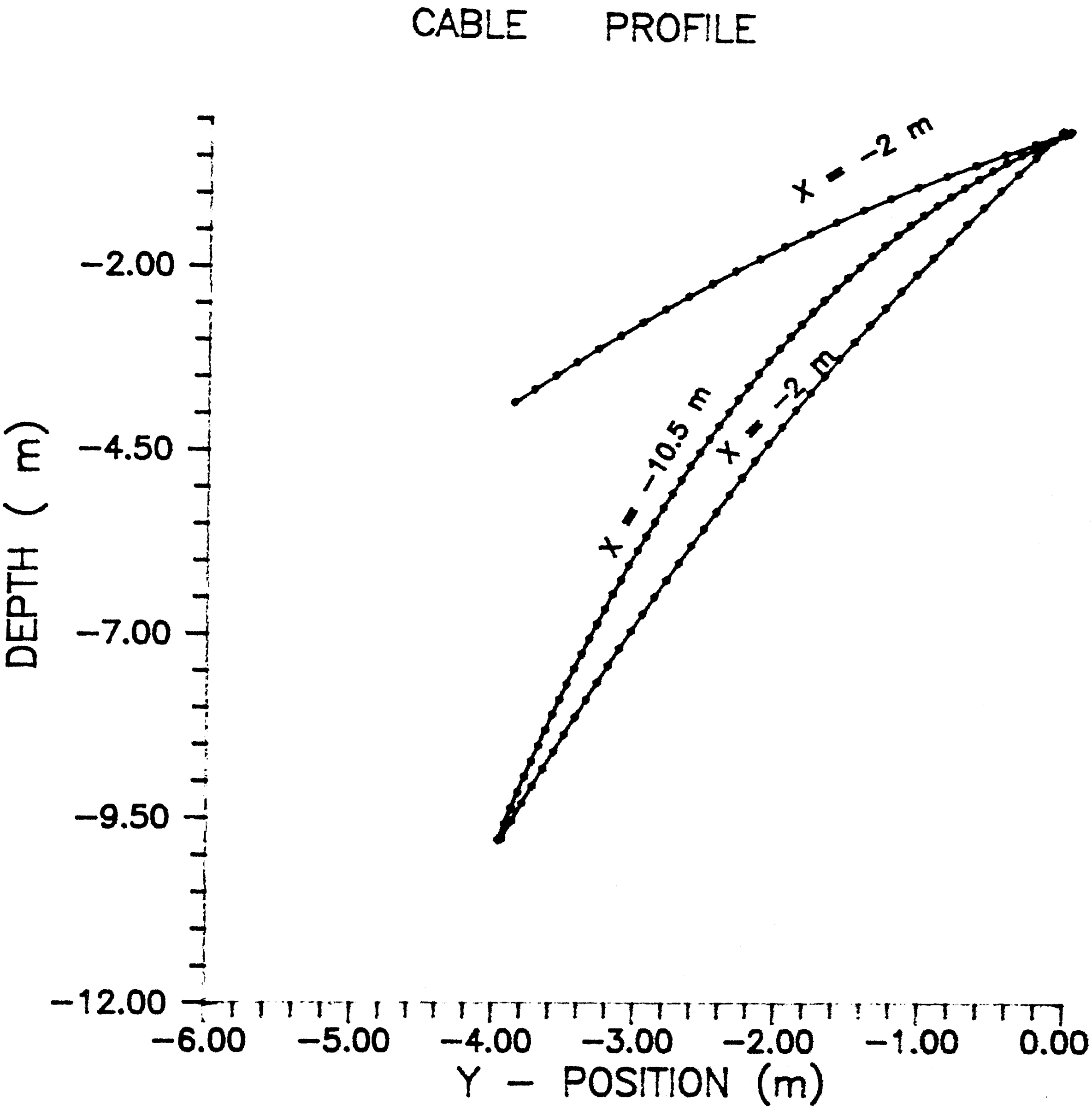


Fig. 6.6b: Cable profile in the Y–Z plane for different positions of the submersible moving in the negative z direction. Total tension = 10 N.

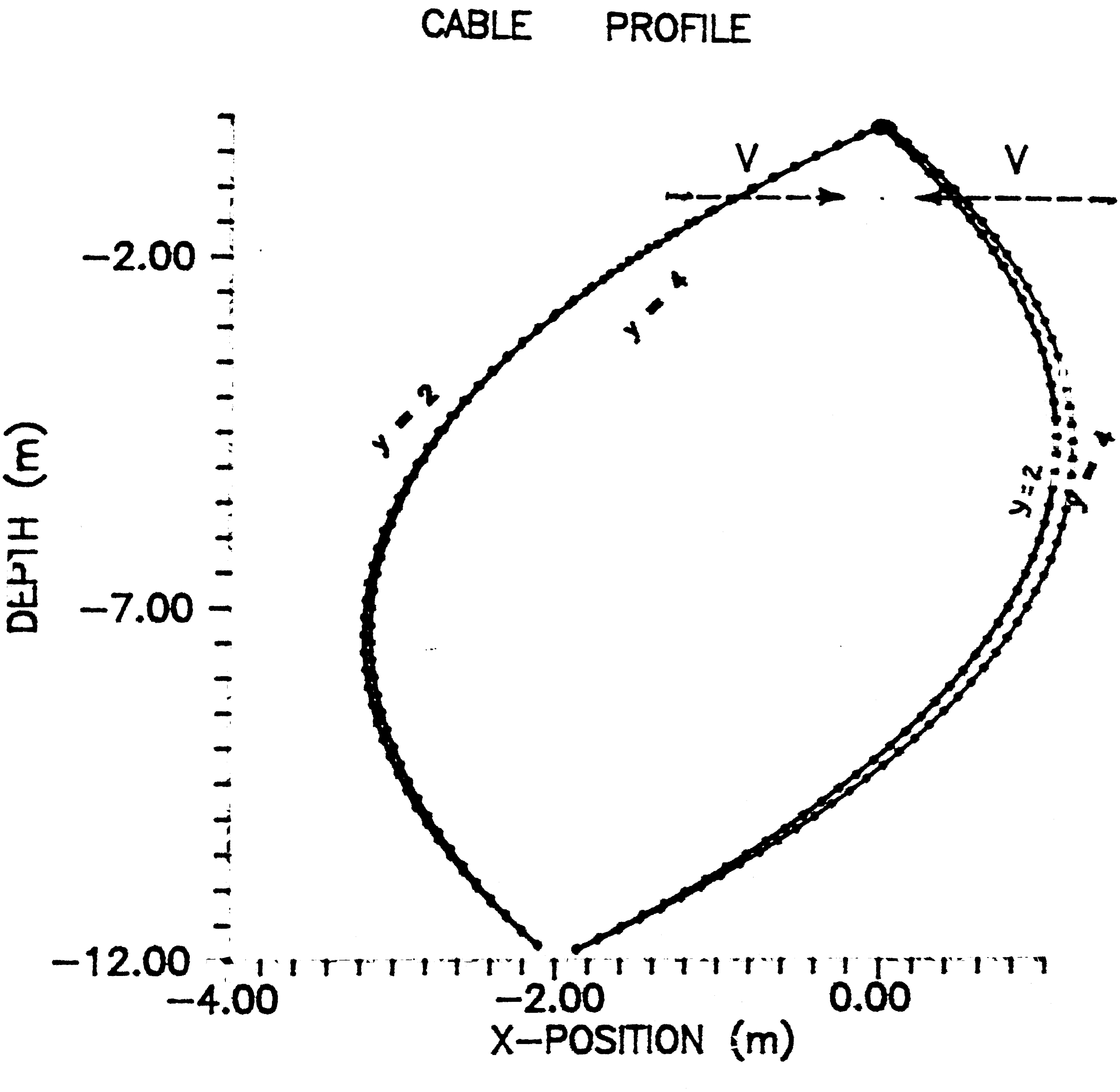


Fig : 6.7a.Graph showing profile of the cable in the X-Z plane when submersible moves with a equal velocity(0.707 m/sec)in X & Y direction.

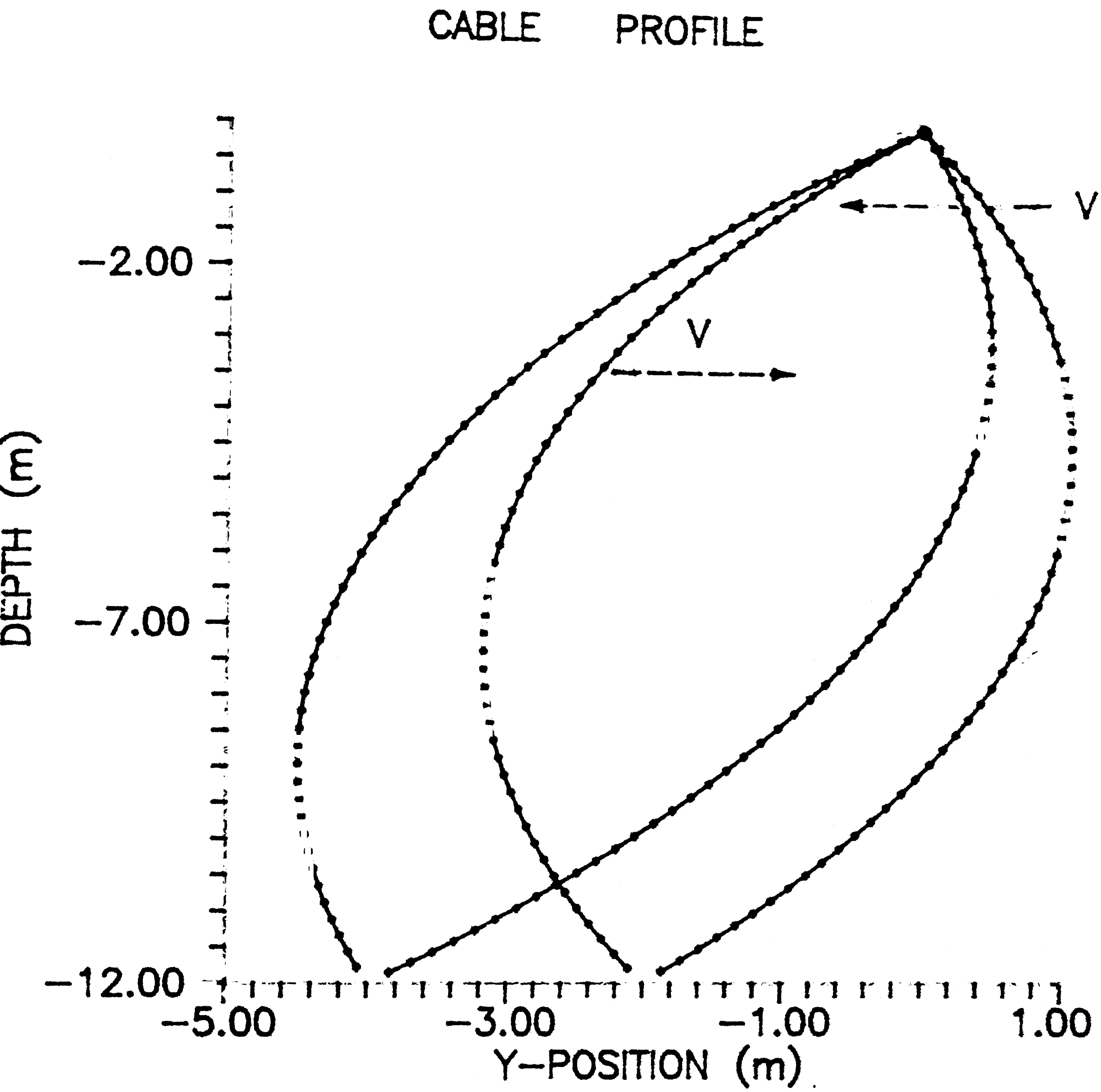


Fig. 6.7b : Graph showing profile of the cable in the Y-Z plane when submersible moves with a equal velocity(0.707 m/sec)in X & Y direction.

CHAPTER VII

VERIFICATION OF DESIGN

7.1 Introduction

The design of the vehicle is verified by checking whether the following conditions are satisfied or not :

a] The thrust provided by the propellers should overcome the drag forces and the cable forces resisting motion.

b] The stepper motors used for the pan and tilt mechanism should provide the required torque.

c] The lights should provide adequate illumination,to facilitate imaging up to 4 m from the vehicle.

d] The vehicle should be neutrally buoyant and the centre of gravity should lie below the centre of buoyancy that is the vehicle should be in equilibrium when at rest.

e] The submersible should move in the desired direction that is the vehicle should be in equilibrium for surge as well as heave motion.

The equations required for calculations of thrust requirement are given in section 5.3 with the procedure outlined

in section 5.4. The equilibrium conditions for the vehicle were identified in chapter 3 while the calculations of drag forces and cable forces is presented in chapter 6 . The required equations and the values of drag forces are taken from these chapters. The equations for stepper motor calculations and underwater light requirement ,calculations are presented in this chapter itself.

7.2 Verification of Selected Propeller

Following the selection procedure outlined in section 5.4 the following propellers were selected ;The horizontal propeller has a diameter of 0.26 m and it's pitch to diameter ratio is 0.67; while the vertical propeller has a diameter of 0.4 m with a P/D ratio of 0.65. This section verifies if the propellers can provide the required thrust and the shaft power required.

. The propeller thrust required to overcome the drag forces, calculated in section 5.2.2 can be calculated by solving the equilibrium conditions established in section 3.4. The relevant equations 3.2 and 3.7 for surge motion and equation 3.10 for heave motion are rearranged and written as :

a] Surge :

$$T_{x1} + T_{x2} = t_{cx} + D_{x1} + D_{x2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7.1)$$

$$T_{x1} - T_{x2} = \frac{t_{cy} * L/2.0}{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7.2)$$

b] Heave :

$$T_z = D_z + t_{cz} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.3)$$

The above equations can be solved to give the values of T_{x1}, T_{x2} and T_z for known values of D_{x1}, D_{x2}, t_{cx}, t_{cy} and t_{cz} calculated in section 6.2.2 and 6.2.3 . Fig 7.1 shows the thrust required to drive the vehicle at speeds from 0.2 to 1 m/sec in the horizontal and vertical direction. The Fig 7.2 shows the shaft horsepower required to develop this thrust at the required velocity. From the power graph it is observed that the horizontal propeller (P_1 and P_2) can provide required thrust to drive the vehicle with a velocity in the range of 0 to 1.0 m/sec . The propeller in the vertical direction (P_3) cannot propel the vehicle with velocity higher than 0.7 m/sec .

7.2.1 Calculations for Thrust Requirement

The sample calculation is given for a vehicle moving at a velocity of 1 m/sec.

Substituting the values of D_{x1}, D_{x2}, D_z , t_{cx}, t_{cy}, and t_{cz} calculated in section 6.2.2 equations 1 and 2 can be solved to give T_{x1} and T_{x2}. L and B are taken as 1.0 and 0.35 respectively .

$$T_{x1} + T_{x2} = 92.75 + 2 + 10 = 104.75$$

$$T_{x1} - T_{x2} = \frac{10 * 1.0/2.0}{0.35} = 14.28$$

Solving the above two equations we get the value of T_{x1} and T_{x2} as 59.52 N and 45.23 N respectively.

Substituting values of F_B, W, D_z and t_{cz} in equation 5 :

$$T_z = 1810 - 1810 + 273.16 + 10 = 283.16 \text{ N.}$$

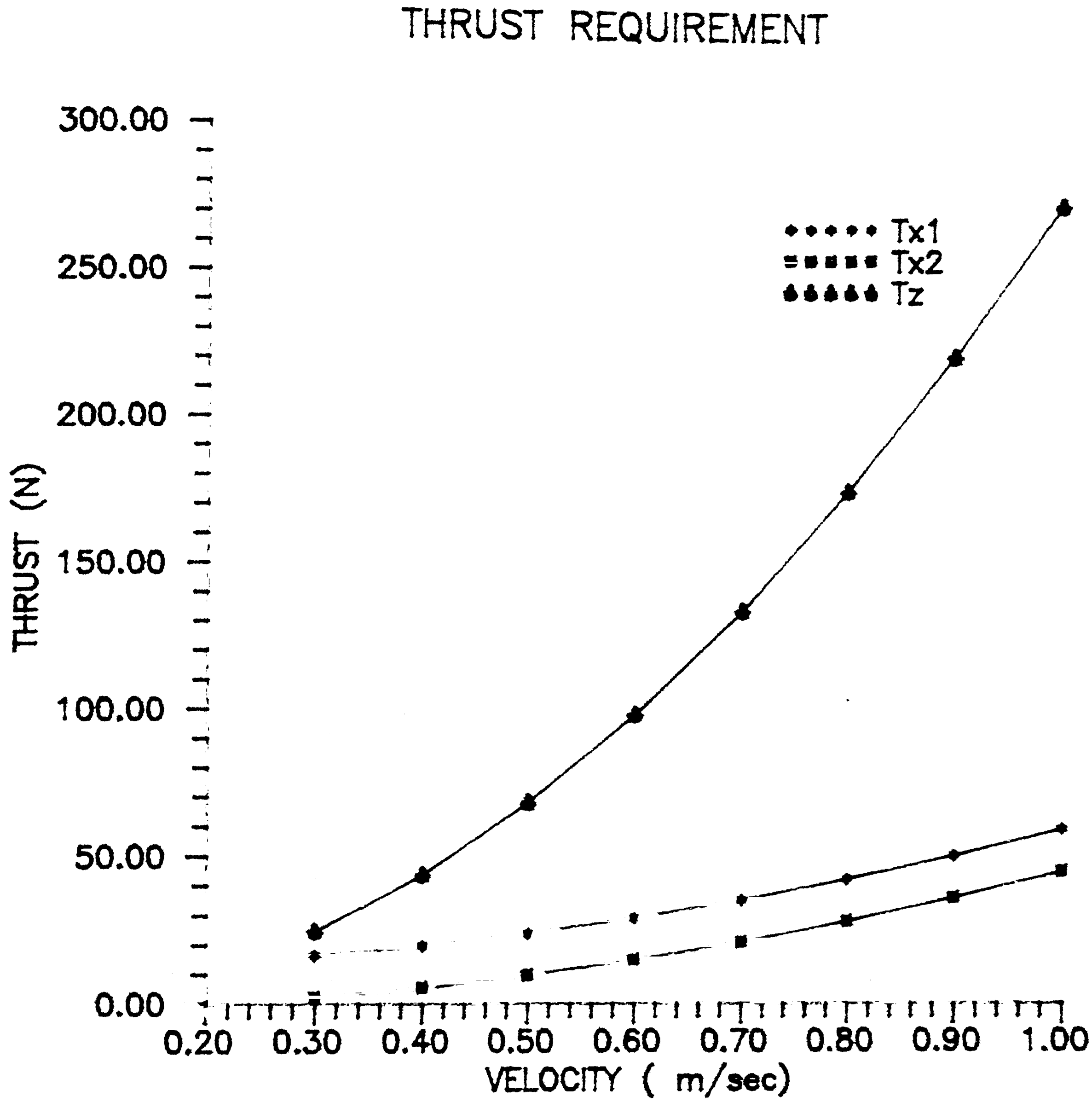


Fig. 7.1 Graph of axial velocity vs the thrust requirement

7.2.2 Calculations for Power Requirement

The procedure to calculate the power required for the selected propellers to provide the required thrust at a given velocity is outlined in section 3.3.1. Following this procedure the power required by the horizontal propeller (P1) and the vertical propeller (P3) is given when the velocity of the vehicle is 1 m/sec

The horizontal propeller has a diameter of 0.26 m and it's pitch to diameter ratio is 0.67; while the vertical propeller has a diameter of 0.4 m with a P/D ratio of 0.65.

a] Calculations for horizontal propeller (P1)

From Taylor's Chart :

η = 0.52 % ; Bp = 39.93 ; J = 0.42

$$k_q = \frac{B_p^2}{33.08^2} * J^5 = \frac{39.91^2}{33.08^2} * 0.42^5$$

$$= 0.018$$

$$K_t = \frac{2.0 * \pi * K_q * \eta}{J} = \frac{2.0 * \pi * 0.018 * 0.52}{0.42}$$

$$= 0.142$$

$$n = \frac{V}{D * J} = \frac{1.0}{0.26 * 0.42}$$

$$= 9.15 \text{ rps}$$

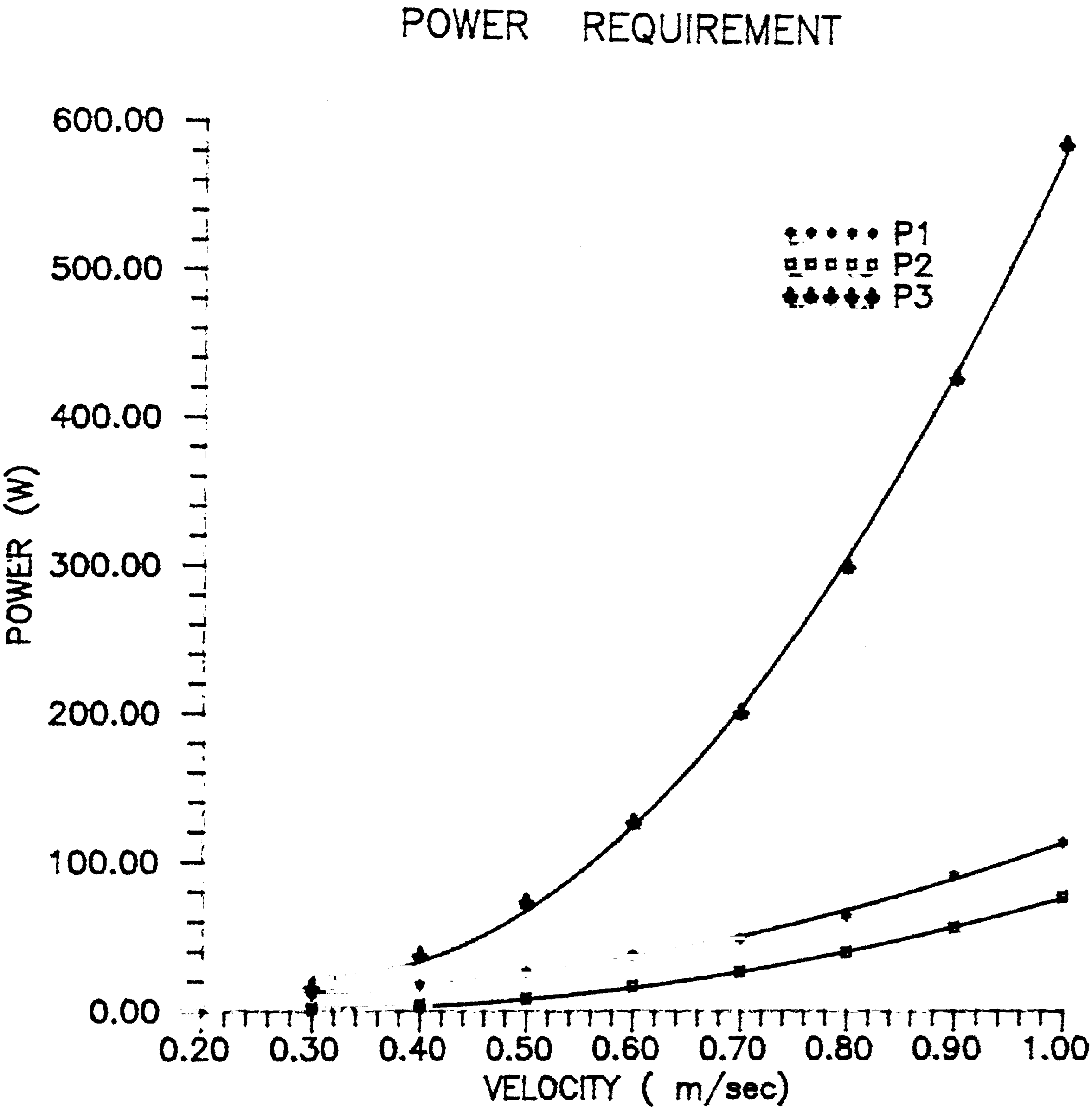


Fig. 7.2 Graph showing the shaft power requirement of the three propellers. Propeller P1 and P2 are along the horizontal axis while P3 is along vertical axis.

$$P = 2.0 * \pi * K_q * \rho * n^3 * D^5$$
$$= 2.0 * \pi * 0.018 * 1046 * 9.15^3 * 0.26^5$$
$$= 107.67 \text{ W.}$$

b] Calculation for Vertical propeller (P_a).

The formulae and the steps followed are same as that for the horizontal propeller . The corresponding values are as follows :

η = 0.445 ; Bp = 74.4 ; J = 0.33

K_q = 0.0198 ; K_t = 0.168

n = 7.5 rps ; P = 562 W .

7.3 Verification of Stepper Motor Torque Requirement.

The specifications of the stepper motors for the pan and tilt mechanism is given in the Table -5 in Appendix - B . The maximum torque provided by the motor is 4 kg cm . The torque of the motor can be calculated by using the expression given below with the notations :

J_l : Load inertia. kg m^2

J_l : Motor inertia. kg m^2

T : Motor Torque N m

α : Angular acceleration. rad/sec^2

ω : Angular velocity rad/sec .

θ : Angular distance travelled in one step rad

$$T = (J_l + J_m) * \alpha \quad \text{.............................(7.4)}$$

$$\alpha = \frac{\omega^2}{2.0 * \theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7.5)$$

It is assumed that the angular velocity of the motor increases linearly while moving from one step to another. Substituting

ω = 0.122 rad/sec^2 and θ = 0.05 rad

in equation 7.5 gives the value of angular acceleration as 2.88 rad/sec^2. The calculations for the load inertia are given in Table - 7.1. The value of load inertia is 0.18 kg m^2. Substitution of these values in equation -7.4 gives the motor torque as 0.024 Nm ie. .24 kg cm . Therefore the stepper motor can provide the required torque.

COMPONENT	MASS (M)	M.I
	Kg	Kg.m^2
Platform	1.24	0.0083
Rev Base	0.87	0.0075
Camera	0.7	0.0025
Motor	2	-0.0014
Σ M.I * M/Σ M	0.18	

Table 7.1 Load Inertia on the Stepper Motor

7.4 Verification of Illuminance Required for Observation

The vehicle is provided with two lights of a power capacity of 100 W each and a initial intensity of 1340 lumens. The specifications of lights are given in Table- 6 in Appendix - B. This section verifies if the light intensity is sufficient to view objects in the range of 4 m from the camera. The following notation is used :

c : Beam attenuation coefficient of water

I : Source luminous intensity candela

L : Illuminance (Lux)

r_1 : Source to object distance. (m)

r_2 : Object to sensor distance. (m)

ρ : Object reflectance.

τ : Water transmittance.

ϕ : Intensity (lumens)

The luminance observed by the underwater camera or the viewer is given by the expression :

$$L = I * \rho * \tau / r_1^2 \quad \text{..................(7.6)}$$

$$\tau = e^{-c * (r1 + r2)} \quad \text{......................(7.7)}$$

Substituting the values of c, r_1, r_2 as 0.1, 4 , 4 respectively in equation 7.7 the water transmittance turns out to be 0.549.

The minimum illuminance required for the camera is 3 Lux as given in it's specifications. Therefore the only unknown in equation 7.6 is the source intensity which can be calculated by

rearranging the equation as :

$$I = \frac{L * r^2}{\rho * \tau} = \frac{3 * 4^2}{0.55 * 0.549} = 158.67 \text{ candela.}$$

The intensity in lumens is given by the expression :

$$\phi = 4.0 * \pi * I \quad \text{.....................(7.8)}$$

The minimum light source intensity should be of the order of 1994 lumens. The two lights provide a intensity of 2680 lumens.

7.5 Verification of Equilibrium Of Vehicle

7.5.1 Hydrostatic Equilibrium

The vehicle should maintain a upright position when it is at rest. The conditions for equilibrium were given in section 3.4.1. Table 7.2 shows that the weight and buoyancy forces are equal and the centre of buoyancy lies above the centre of gravity with both lying in the same vertical plane ie. their line of actions coincide. Hence the conditions for hydrostatic equilibrium are satisfied.

7.5.2 Equilibrium in Steady Steady State motion

The equilibrium condition of the vehicle were given in section 3.3.1 surge and in section 3.3.2 for heave motion. Investigation of these equations show that the sum of the forces (Σ Fy = 0 ; equation 3.4) and the sum of moments in the Y- direction (Σ My = 0 ;equation 3.7) are not zero since tcy is not zero and the direction of Dx2 can be same as that of tcy.

COMPONENT	WEIGHT	BUOYANT FORCE	C.G			C.B		
			X	Y	Z	X	Y	Z
	N	N	cm	cm	cm	cm	cm	m
Hull	783.4	1433	-1.5	0	0	4.4	0	0
Motor Assembly 1,2	563	333	-2.0	0	0	8.0	0	0
Motor Assembly 3	220	9.8	0	0	7.5	0	0	2.6
Pan & Tilt Mech.	98	-	26	0	5	-	-	-
Detector	2.5	-	10	0	20	-	-	-
Lights	5	-	40	0	0	-	-	-
Panel Board	20	-	36	0	0	-	-	-
Coupling	10	-	50	0	0	-	-	-
Dead Weight	73	-	19	0	20	-	-	-
Total	1775	1775	14	0	16	14	0	0.1

Table 7.2 Position of Centre of Gravity and Centre of Buoyancy.

The effect of the unbalanced force tcy is to cause the vehicle to move in the direction perpendicular to the direction of motion. To avoid this the vehicle axis should be at an angle β with the direction of motion . To enable the vehicle to move in a straight line the vehicle axis,and the direction of motion should not coincide. The axisymmetry of flow is then lost and the vehicle will be subjected to drag forces in the Y direction. To get a priliminary estimate the drag force is taken same as when the vehicle is moving straight and the Y direction forces are neglected.

a] Surge motion

The angle (β_h) the vehicle should take for surge motion can be calculated by using the equation given below with reference to Fig. 7.3 [a].

$$(Tx_1 + Tx_2).* \cos\beta_h = tcx + Dx \quad \text{.........................(7.9)}$$

$$(Tx_1 + Tx_2) * \sin\beta_h = tcy \quad \text{..............................(7.10)}$$

$$(Tx_1 - Tx_2) * b = \frac{L}{2.0} * \left[\sin\beta_h * (Dx - tcx) + tcy * \cos\beta_h\right]$$

$$\text{...............................(7.11)}$$

Substituting the following values in the above equations :

Dx = 94.75 N ,tcx = tcy = tcz = 10 N and L = 1.0 m the calculated values of Tx_1 ,Tx_2 and the angle β_h are 65.24 N ,39.51 N and 5.45° respectively.

b] Heave

Fig 7.3 [b] shows the forces acting on the vehicle for motion in the vertical direction with the vehicle axis at an angle (β_v) with the X axis. The equilibrium equations can be written as :

$$(Tx_1 + Tx_2) * \cos \beta_v = tcx \quad \ldots\ldots(7.12)$$

$$(Tx_1 + Tx_2) * \sin \beta_v = tcy \quad \ldots\ldots(7.13)$$

$$(Tx_1 - Tx_2) * b = \frac{L}{2.0} \left[- \sin \beta_v * tcx + tcy * \cos \beta_v \right] \quad \ldots\ldots(7.14)$$

Substituting values of tcx, tcy, L, b as 10 N, 10 N , 1.0 m, 0.35 m respectively ,the values of Tx_1 , Tx_2 and β_v are calculated as 5 N, 5 N and 45° respectively.

The effect of the unbalanced moment in the Y - direction is to tilt the vehicle such that it makes an angle α with the horizontal axis in the vertical plane. This angle in the worst case is calculated for the vehicle moving with an velocity of 1 m/sec horizontal direction and with an velocity of 0.7 m/sec in the vertical direction by solving the equations given below with reference to Fig 7.4 [a] and Fig 7.4 [b] :

a] Surge Motion

$$\Sigma My_h = tcy * \frac{L}{2.0} + Dx_2 * c = W * a * \sin \alpha \ldots(7.15)$$

b] Heave Motion

$$\Sigma My_v = tcy * \frac{L}{2.0} = W * a * \sin \alpha \ldots\ldots(7.16)$$

The equations can be solved by substituting the following values :

$tcz = 10$ N ; $Dx_2 = 2$ N ; $L = 0.5$ m

$a = 0.016$ m ; $c = 0.3$ m

giving the values of α_h and α_v as 1.1° and 1.0° respectively .

SURGE MOTION

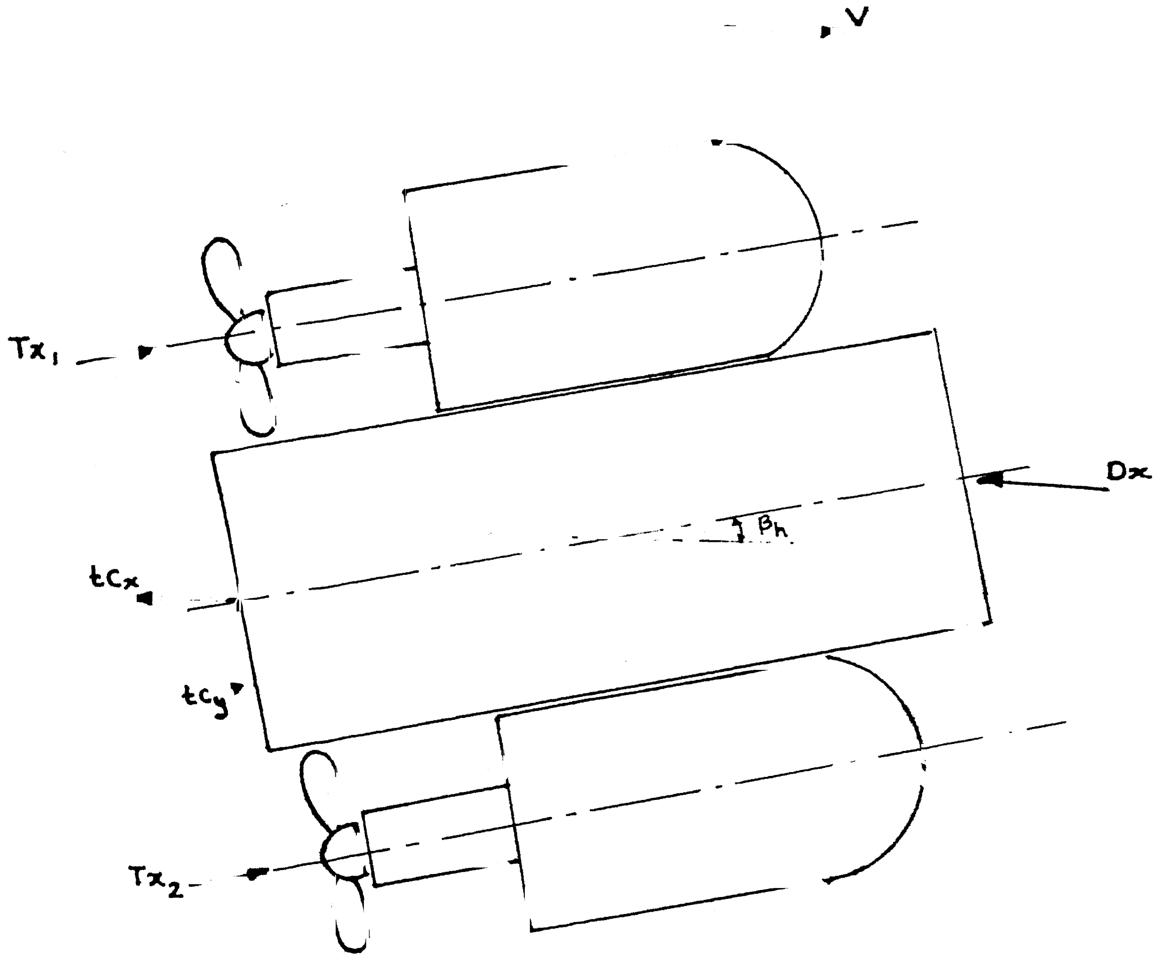


FIG. 7.3a CORRECTION FOR YAW MOMENTS

HEAVE MOTION

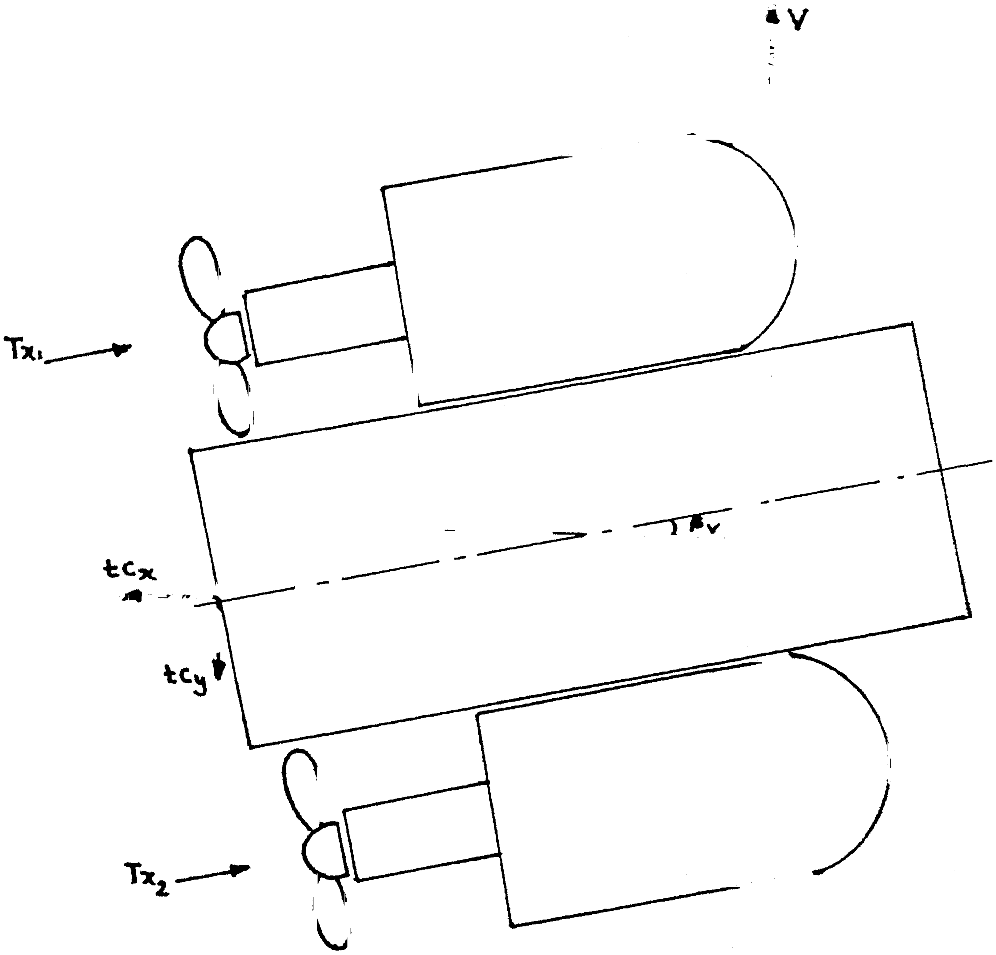
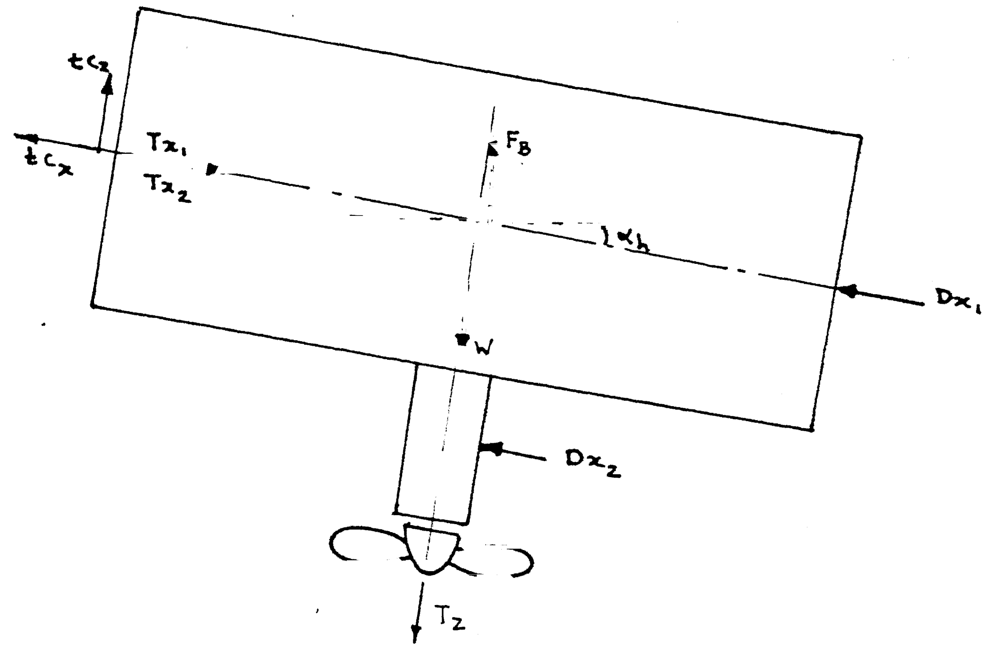


FIG. 7.3 CORRECTION FOR YAW MOMENTS

SURGE MOTION

[a]



HEAVE MOTION

[b]

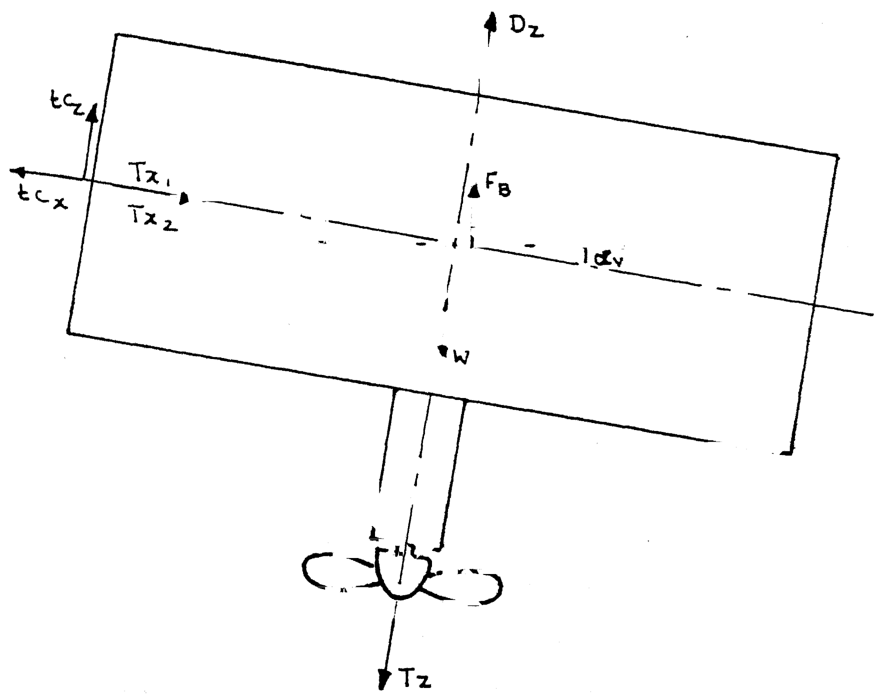


FIG. 7.4 EFFECT OF PITCH MOMENTS

7.6 Conclusion

The thrust provided by the propellers is adequate to drive the vehicle with a velocity in the range of 0 - 1.0 m/sec for surge motion and between 0 - 0.7 m/sec for heave. The lights allow images to be taken at a distance of 4 m from the camera. The stepper motors are capable of providing the necessary torque for the pan and tilt motion. Though the vehicle axis and the axis of motion do not coincide the vehicle can be steered in the desired direction without any drift assuming steady state conditions. The equilibrium conditions for the vehicle are satisfied.

CHAPTER VIII

CONCLUSION

The design of an unmanned, tethered, remotely controlled submersible for the inspection of spent fuel storage tanks in nuclear fuel plants is feasible. The size and weight of the vehicle is comparable to that of the other existing submersibles, used for similar applications.

Most of the other existing vehicles,have an open space metal framework structure. The closed framework structure of the designed submersible reduces possibilities of cable entanglement with the vehicle and eliminates the need to use underwater equipment. The cable attachment position is such that the vehicle is not subjected to any rolling motions ,while the yaw motion created by it can be corrected by using the two horizontal propellers.In case of open space framework structure the cable attachment is usually at the top subjecting the vehicle to rolling couple which has to be corrected by use of two vertical propellers ,thus requiring minimum four propellers. The mounting of the camera on the pan and tilt mechanism enables observation in all directions without changing the position of the vehicle.

Though the vehicle has been designed with inspection of storage tanks as the major application it may be used for inspection of water intake and outlet pipelines,in nuclear as well as thermal and hydroelectric power plants. The vehicle may also be used in offshore industries for inspection at shallow depths.

The following aspects of design will have to be worked on before the vehicle can be fabricated :

a] The details of the control strategy have to be worked out. The interpretation of sensor data shouldn't be left completely on the operator since his attention will be occupied in guiding the vehicle through the desired path.

b] The cable forces for steady state motion have to be studied without the assumption that cable velocity is half that of vehicle velocity. The stiffness of the cable should also be taken into account.

c] For yaw motion correction by the propellers,the drag forces acting on the vehicle in the direction perpendicular to the motion of the vehicle should be considered.

d] The forces acting on the vehicle during unsteady state have to be estimated. The dynamic state cable configuration and the resulting force on the vehicle should be investigated for setting the limits on the torque sensor measuring the cable tension.

e] The performance of the propellers has to be investigated and its effect on the vehicle performance should be studied.

f] The stress analysis of the vehicle structure should be carried out.

g] The reliability analysis of the overall vehicle system will be an important aspect requiring attention.

APPENDIX - A

DETAIL PARTS DRAWINGS OF THE SUBMERSIBLE VEHICLE

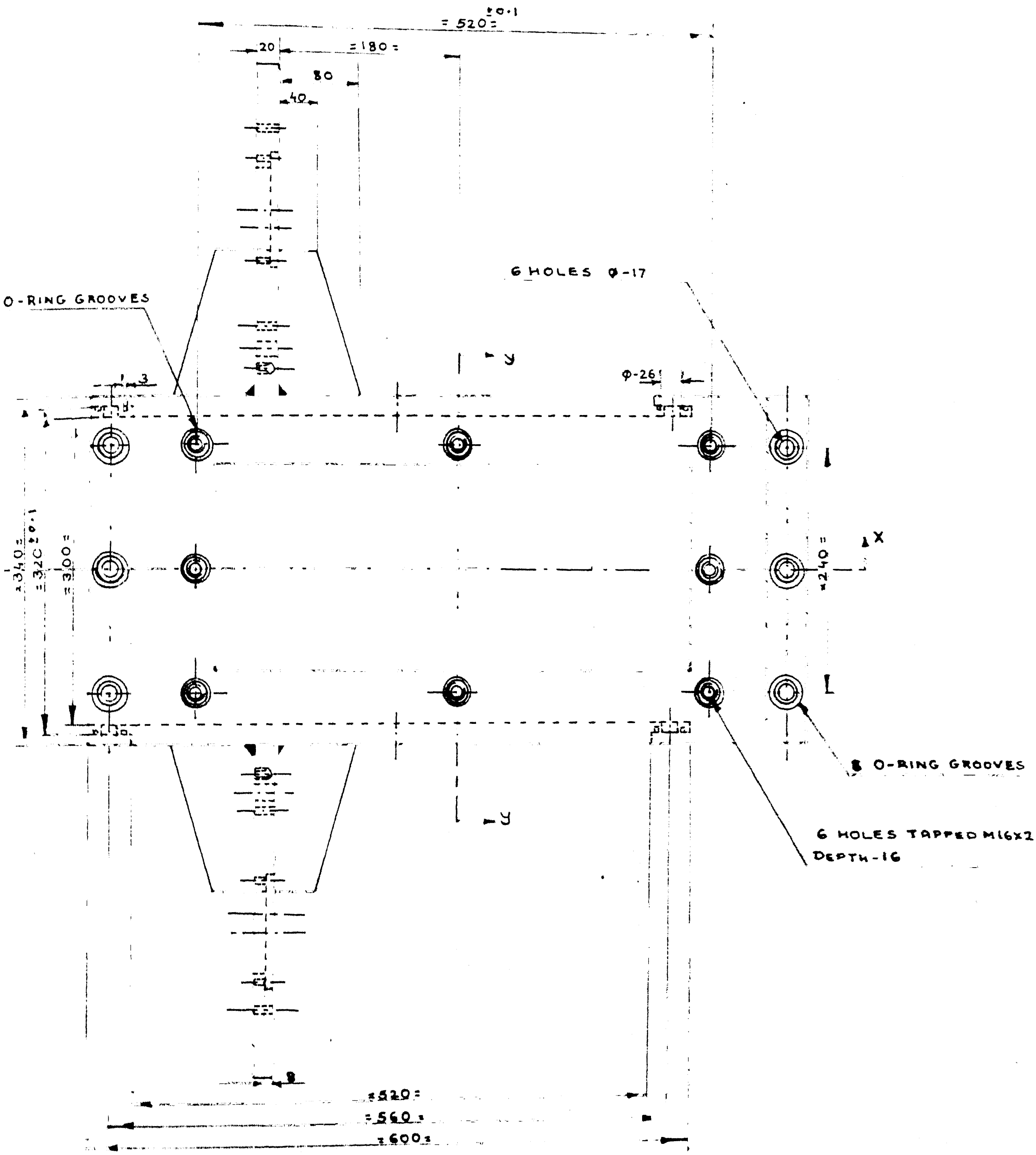


FIG. 2a BUOYANCY TANK P. No. 4

SECTION-YY

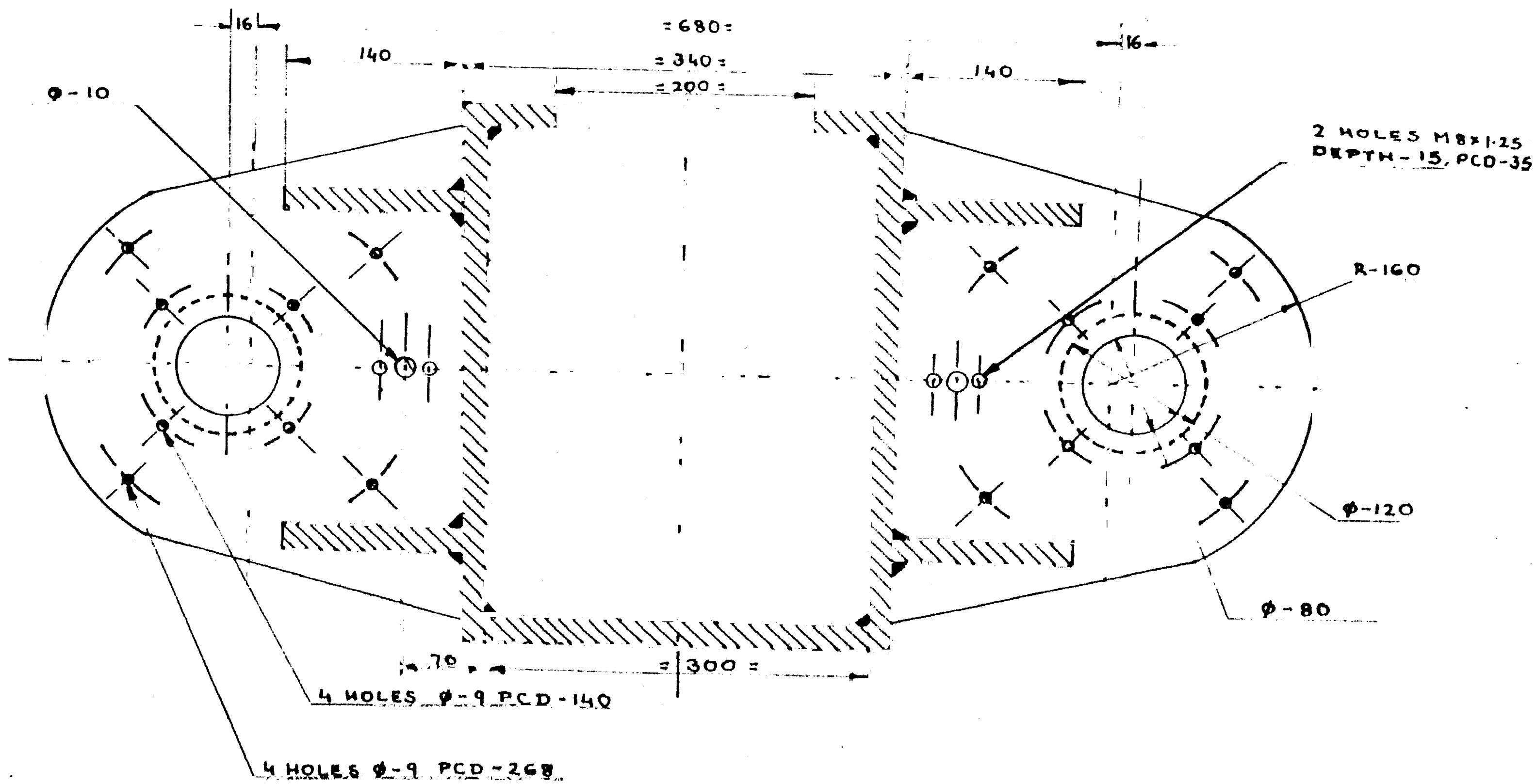


Fig. 1b Buoyancy Tank

P. No. 4

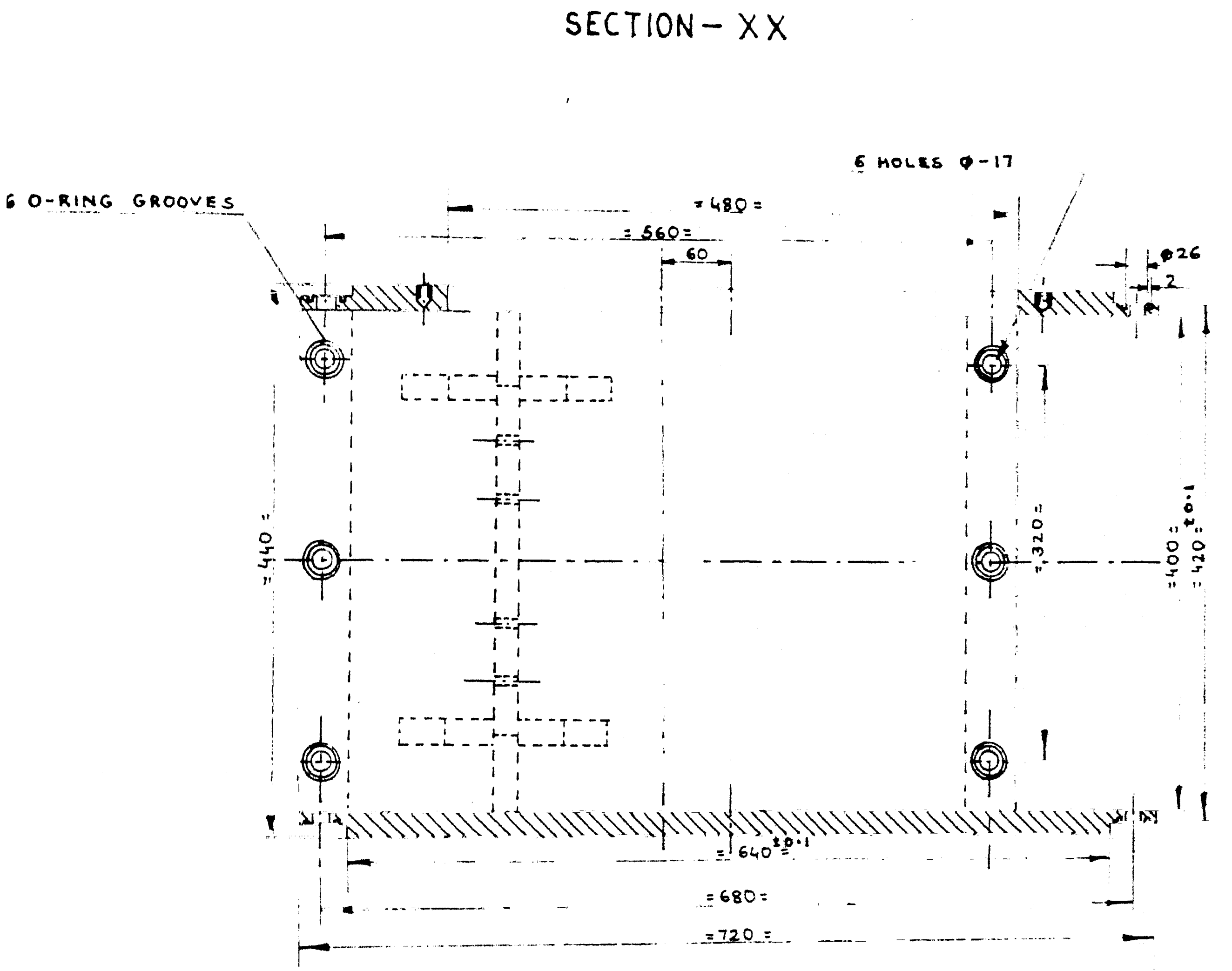


FIG. 2C BUOYANCY TANK P. No. 4

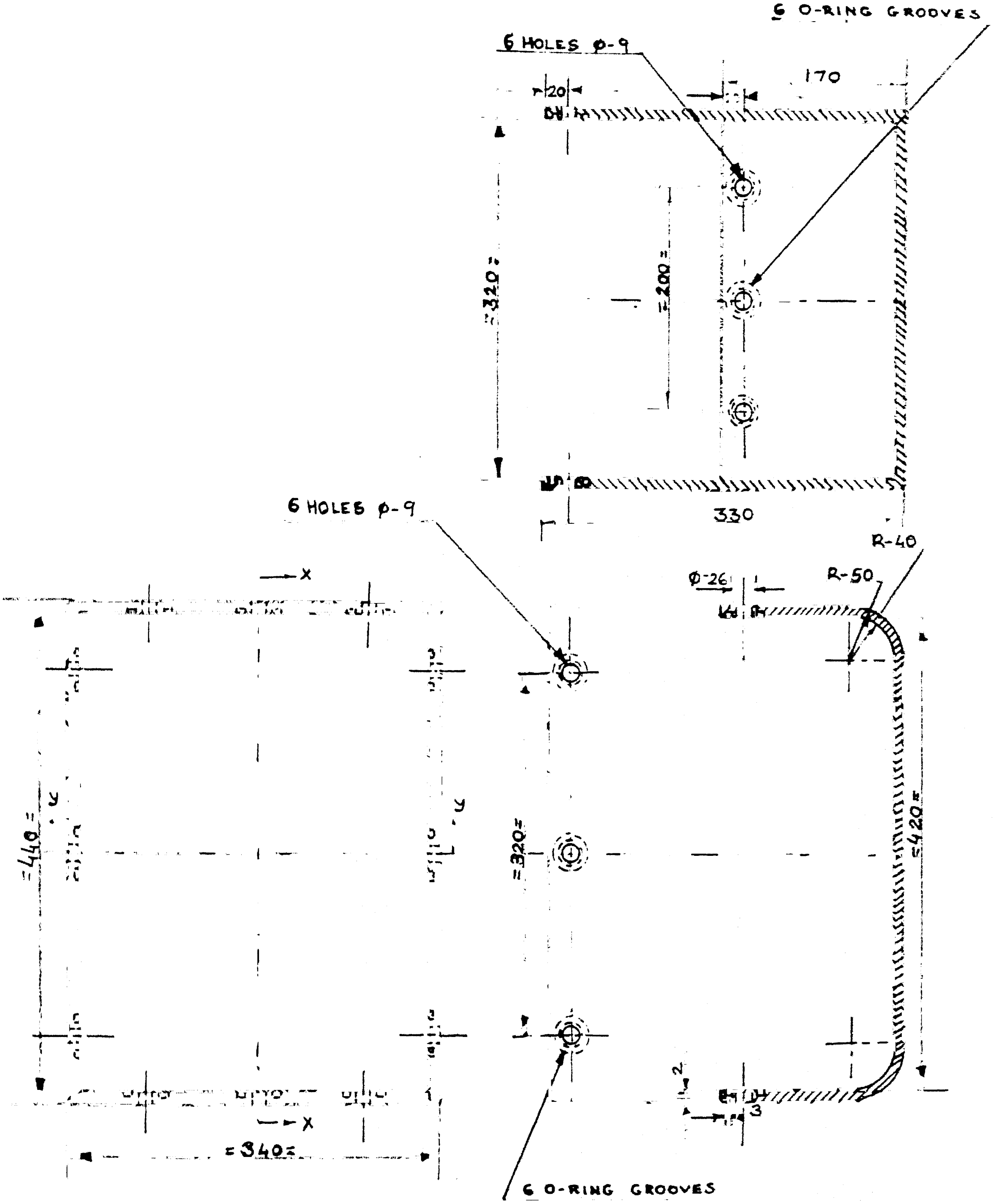


FIG. 2 FRONT COVER P. No. 1

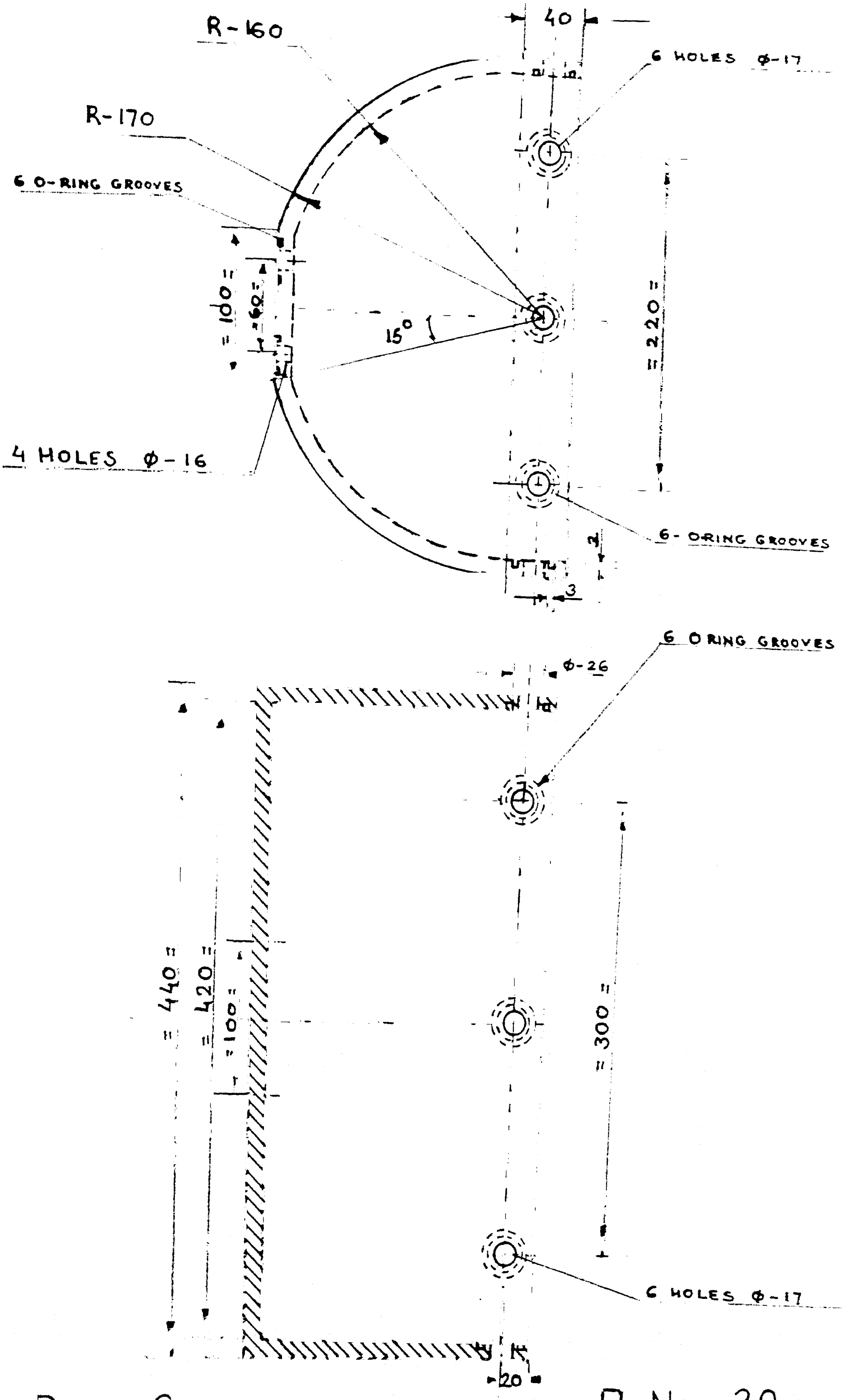


FIG. 3 BACK COVER

P. No. 20

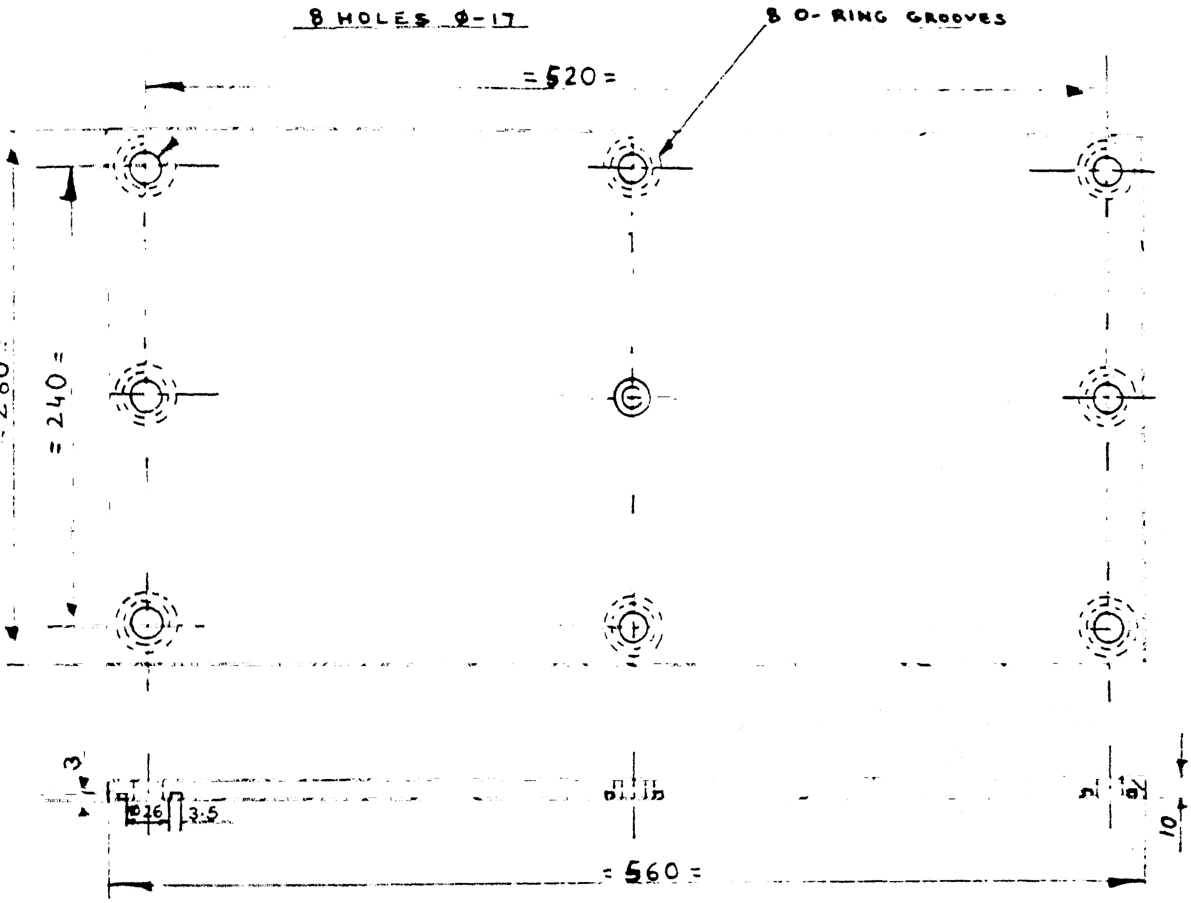


FIG. 4 MANHOLE COVER P. No. 29

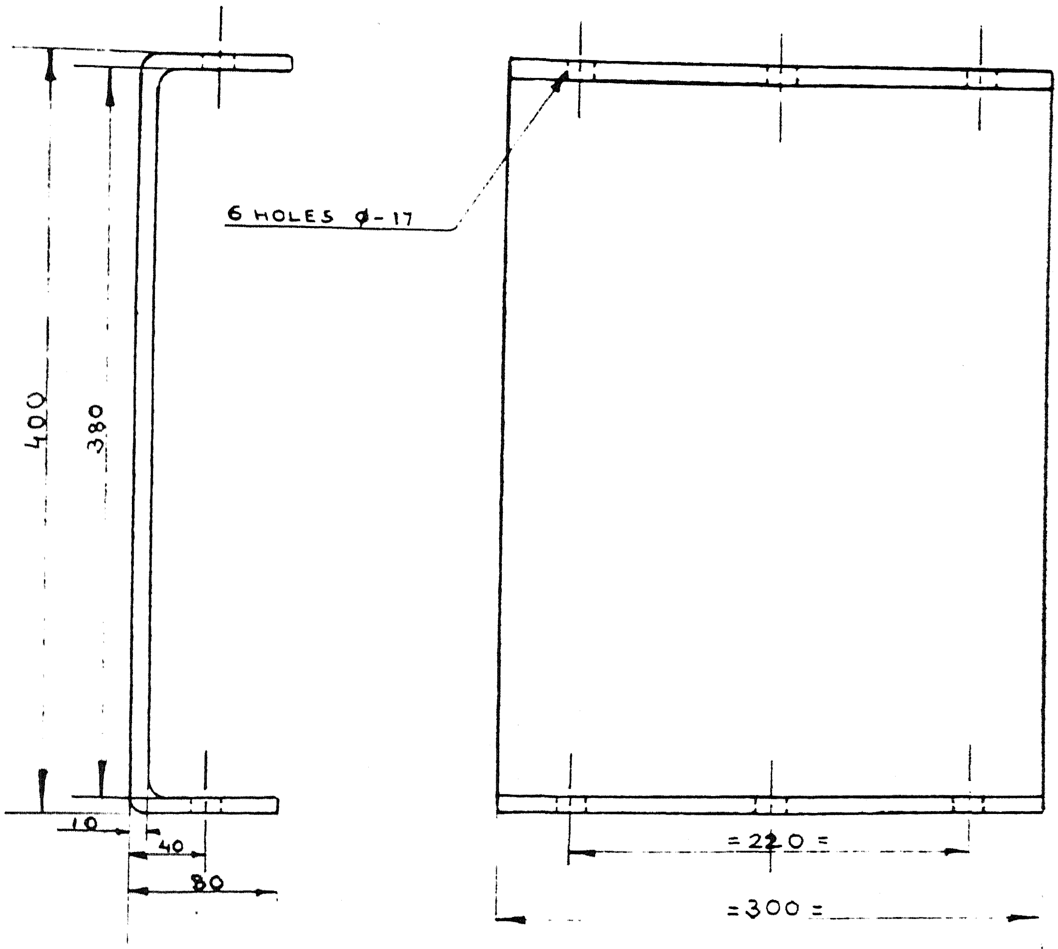
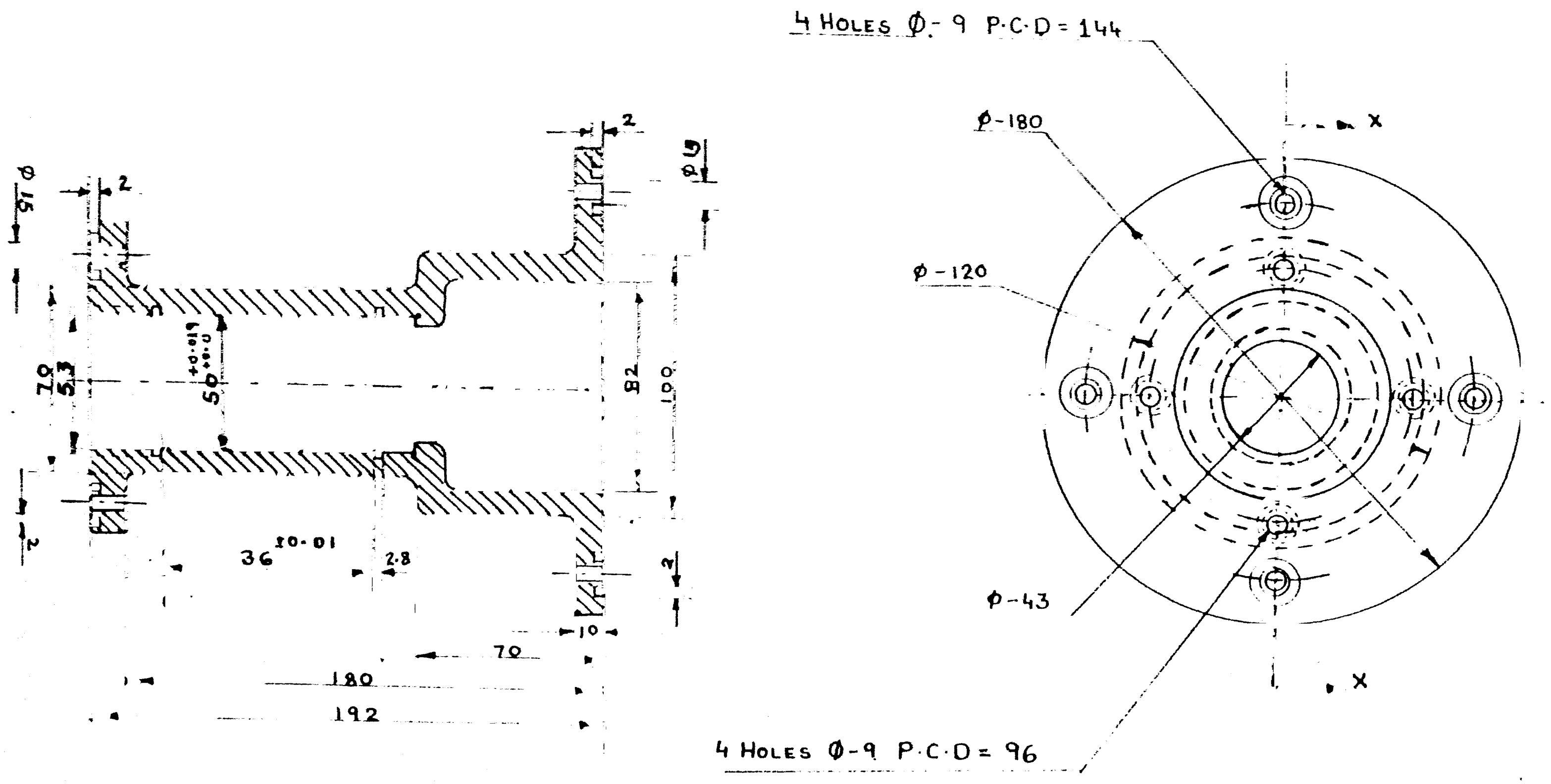


FIG. 5 PANEL BOARD



SECTION XX

FIG. 6 PROPELLER SHAFT HOUSING P. No. 7

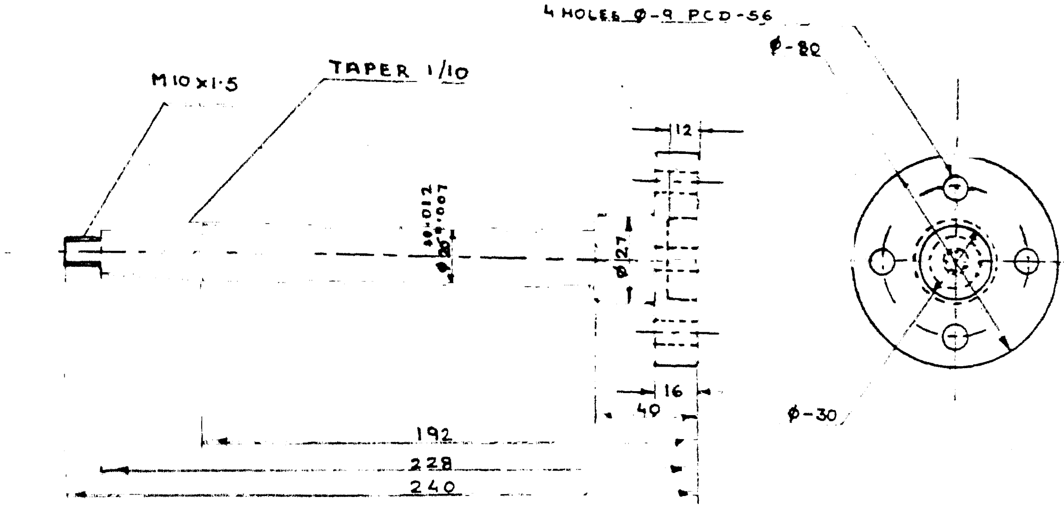


FIG. 7 PROPELLER SHAFT P. No. 10

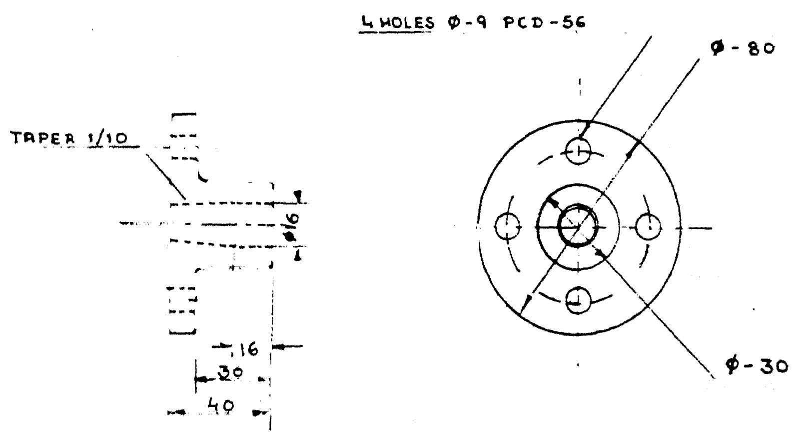


FIG. 8 MOTOR SHAFT EXTENSION P. No. 9

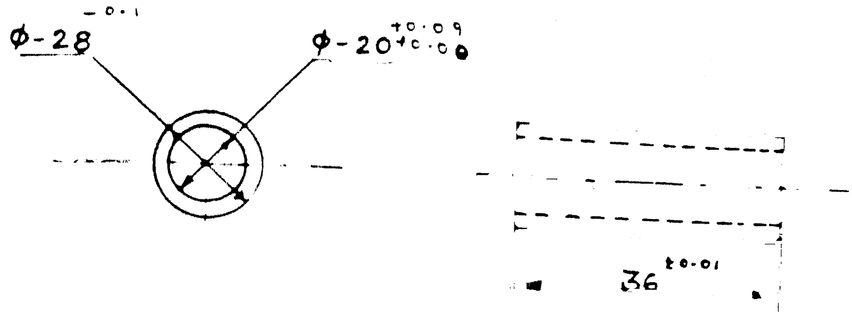


FIG. 9 SLEEVE P. No. 16

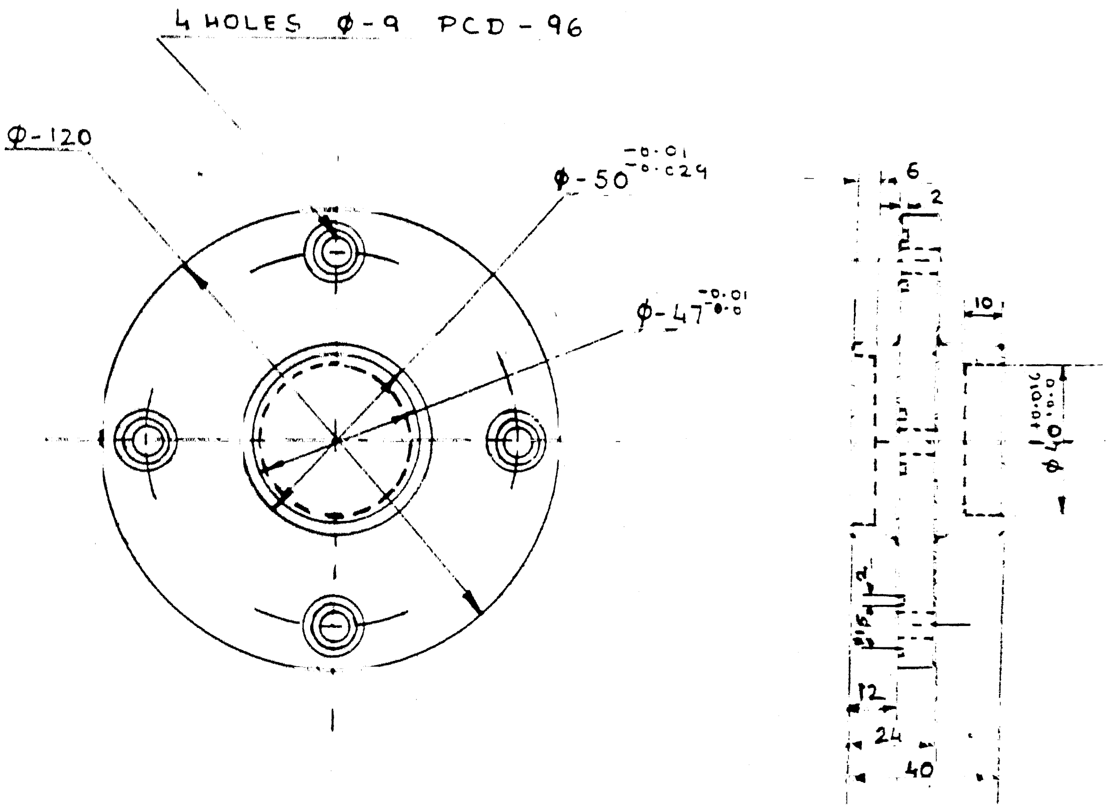


FIG. 10 HOUSING COVER P.No. 13

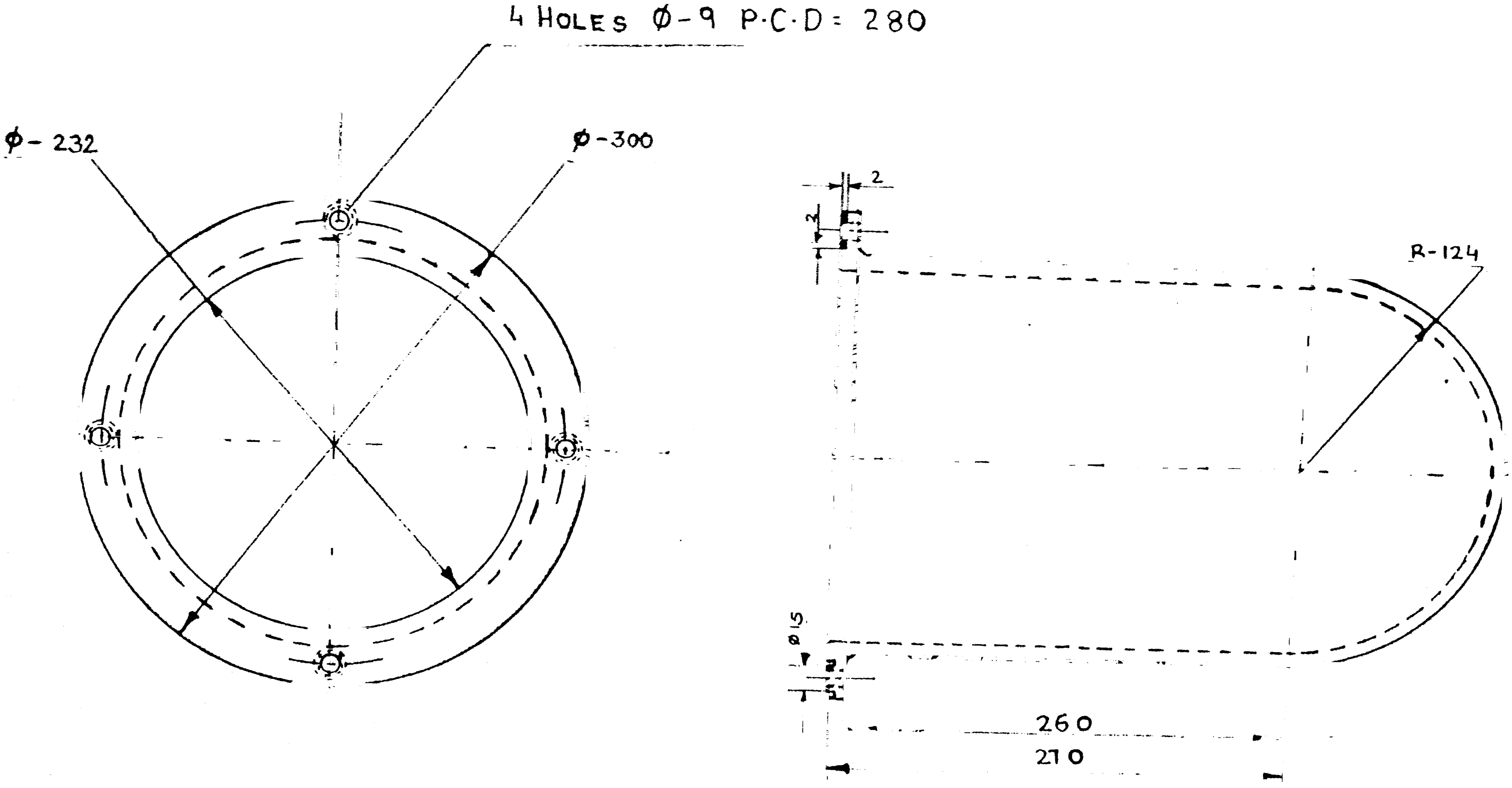


FIG. 11 MOTOR COVER

P. No. 24

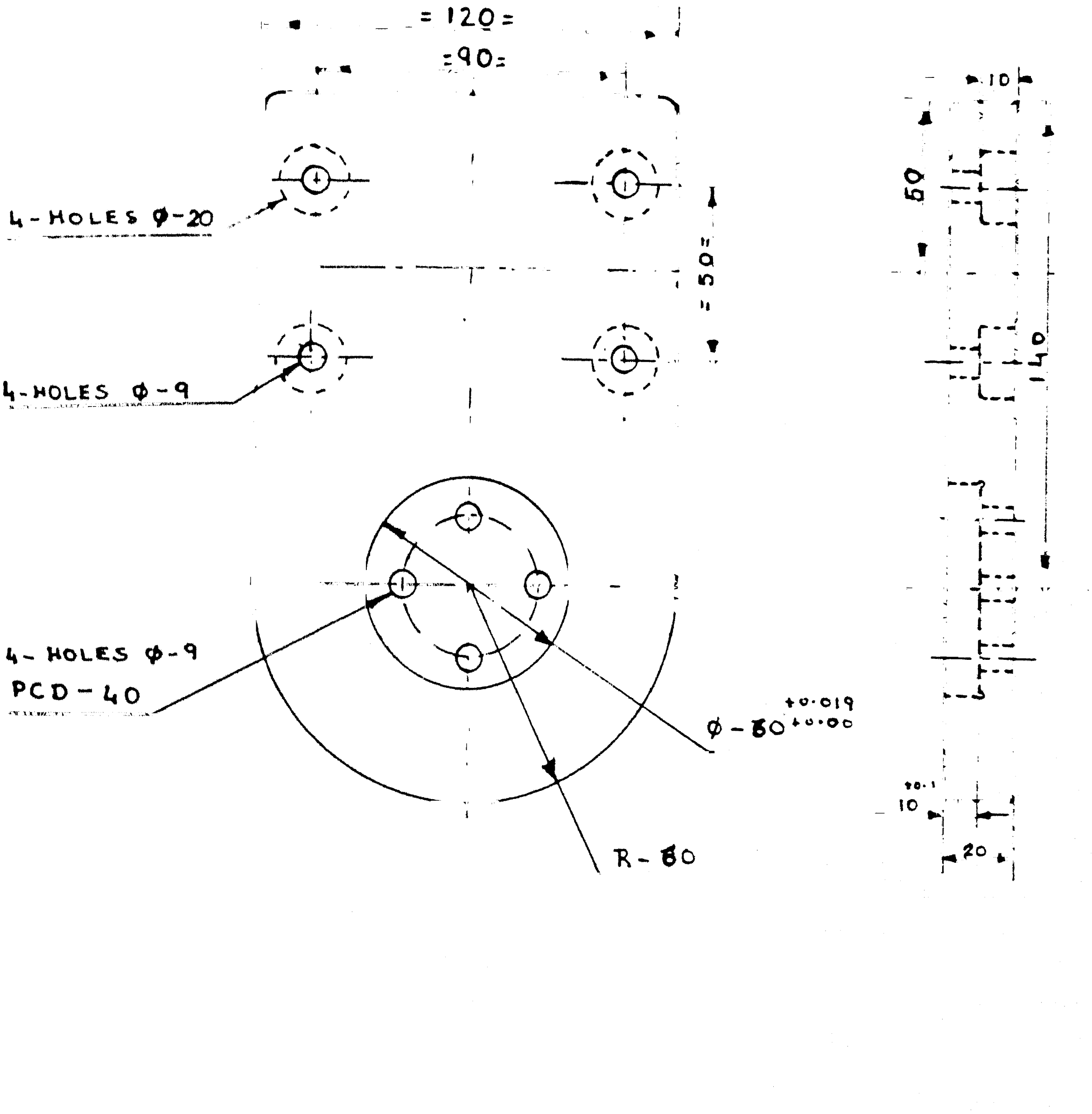


FIG. 12 CAMERA BASE P. No. 2

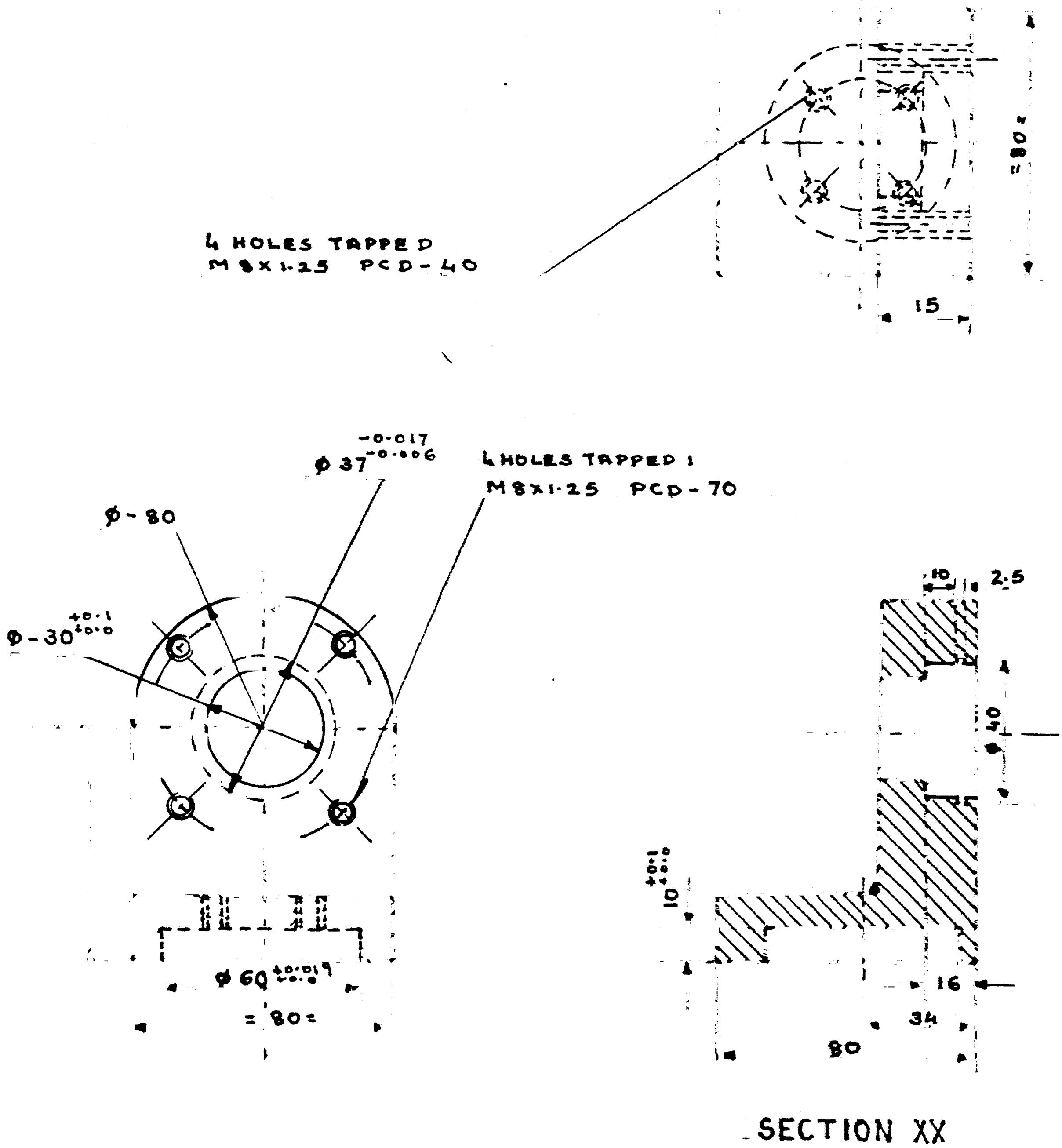


FIG. 13 ROTATING BASE P. No. 11

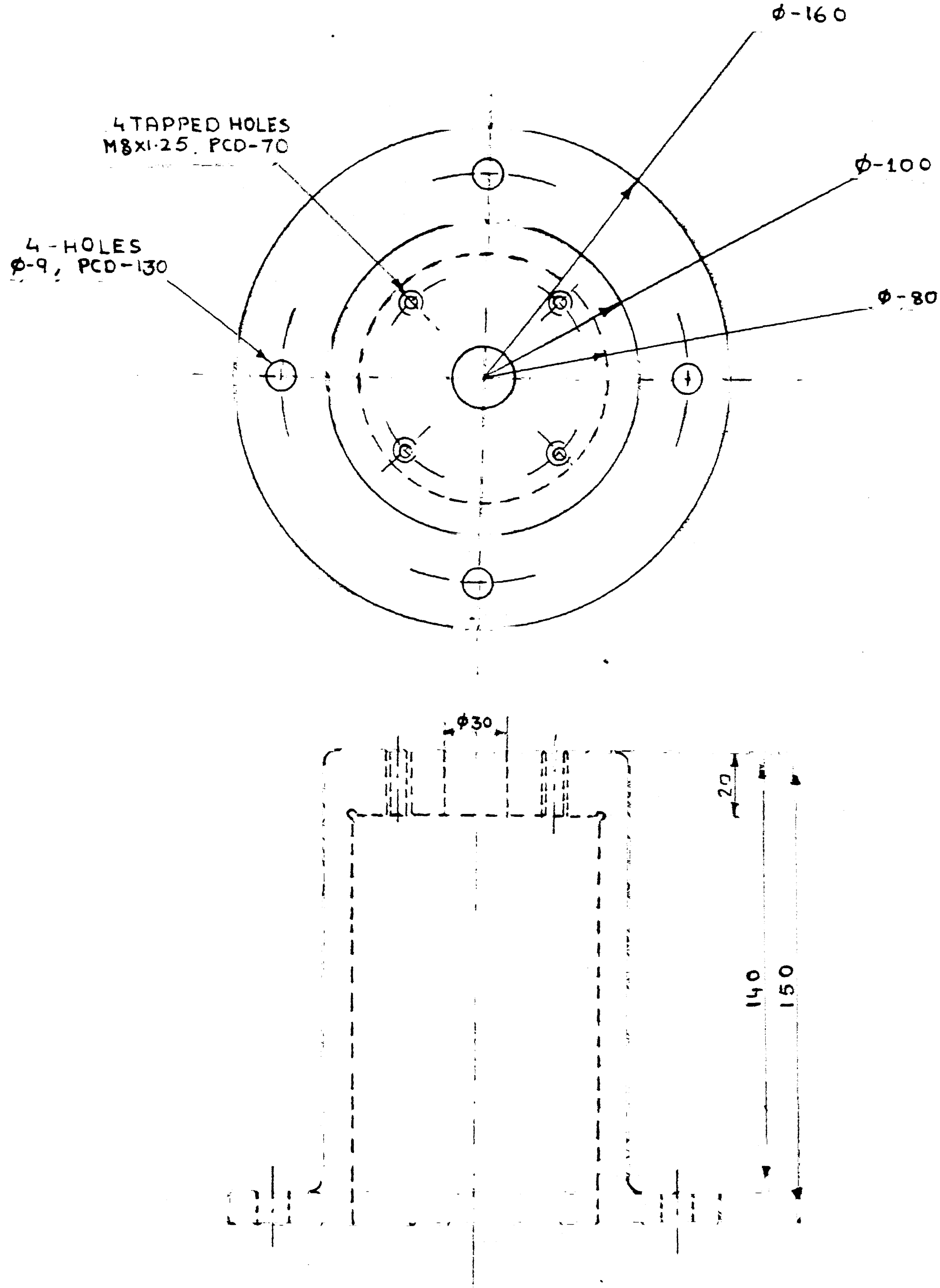


FIG. 14 FIXED. BASE

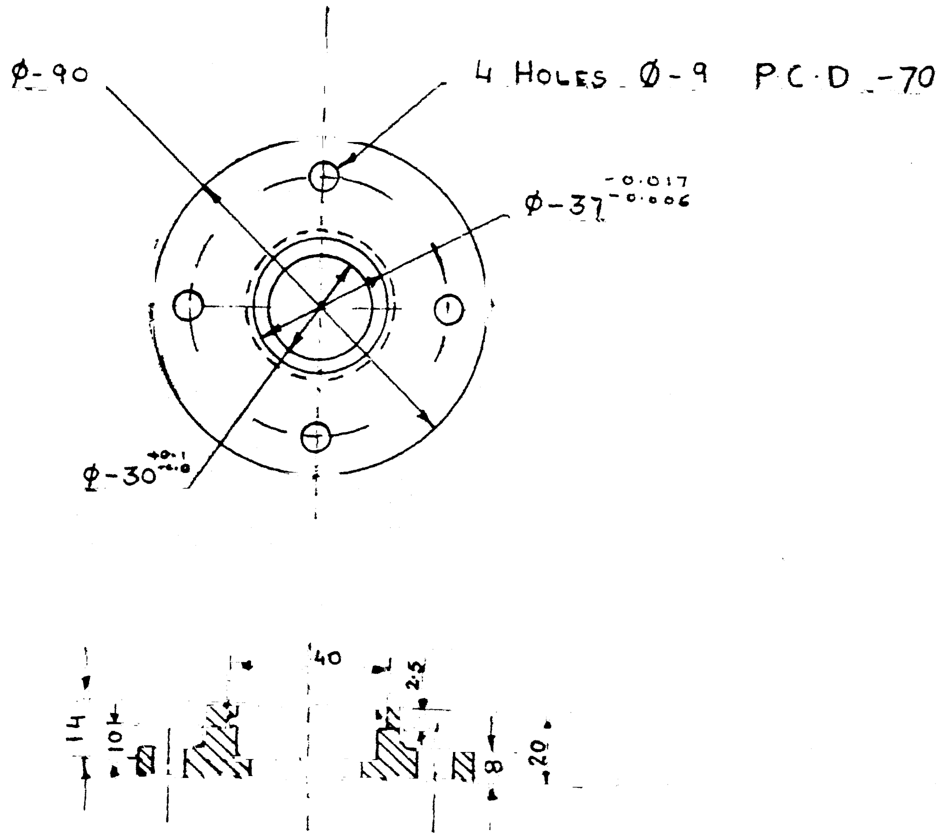
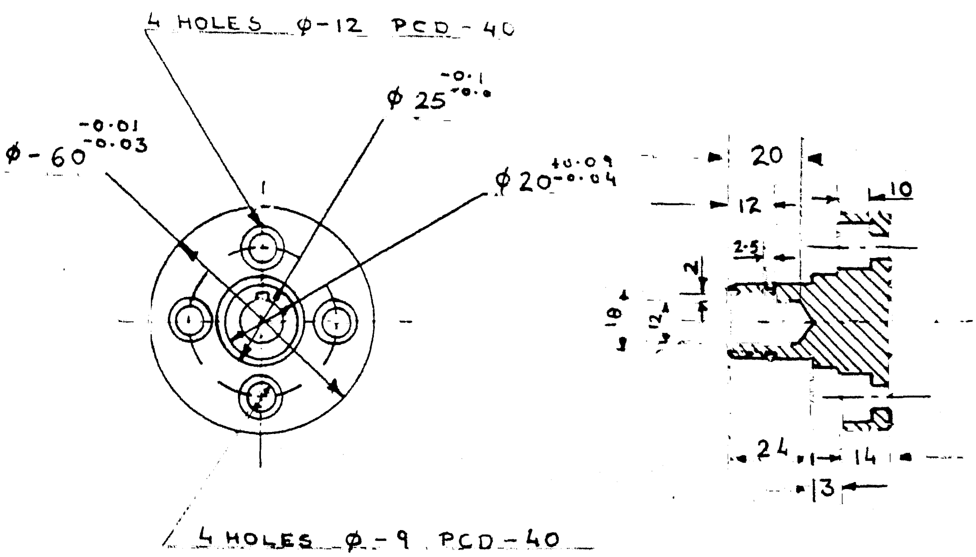


FIG. 15 BEARING HOUSING P.No. 16

FIG. 16 SHAFT EXTENSION P.No. 6 & 14



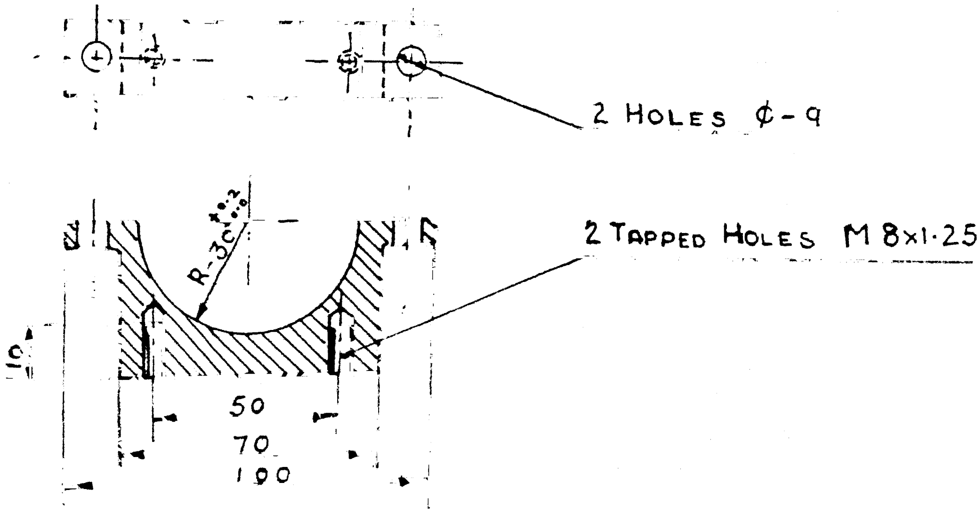


FIG. 17 b MOUNTING BRACKET P. No. 3B

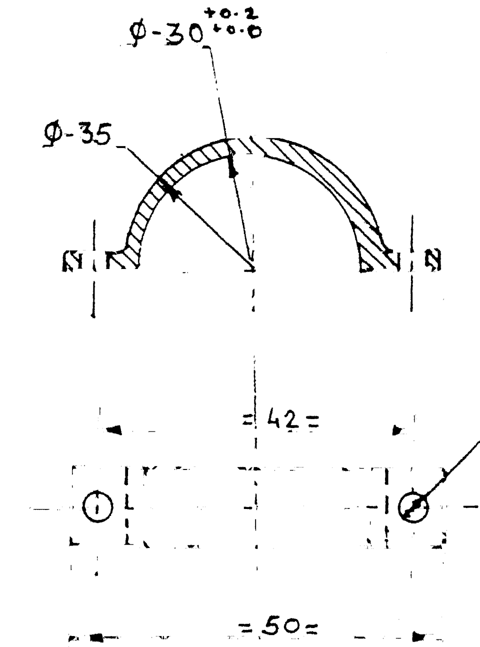


FIG. 17a BRACKET P. No. 3A

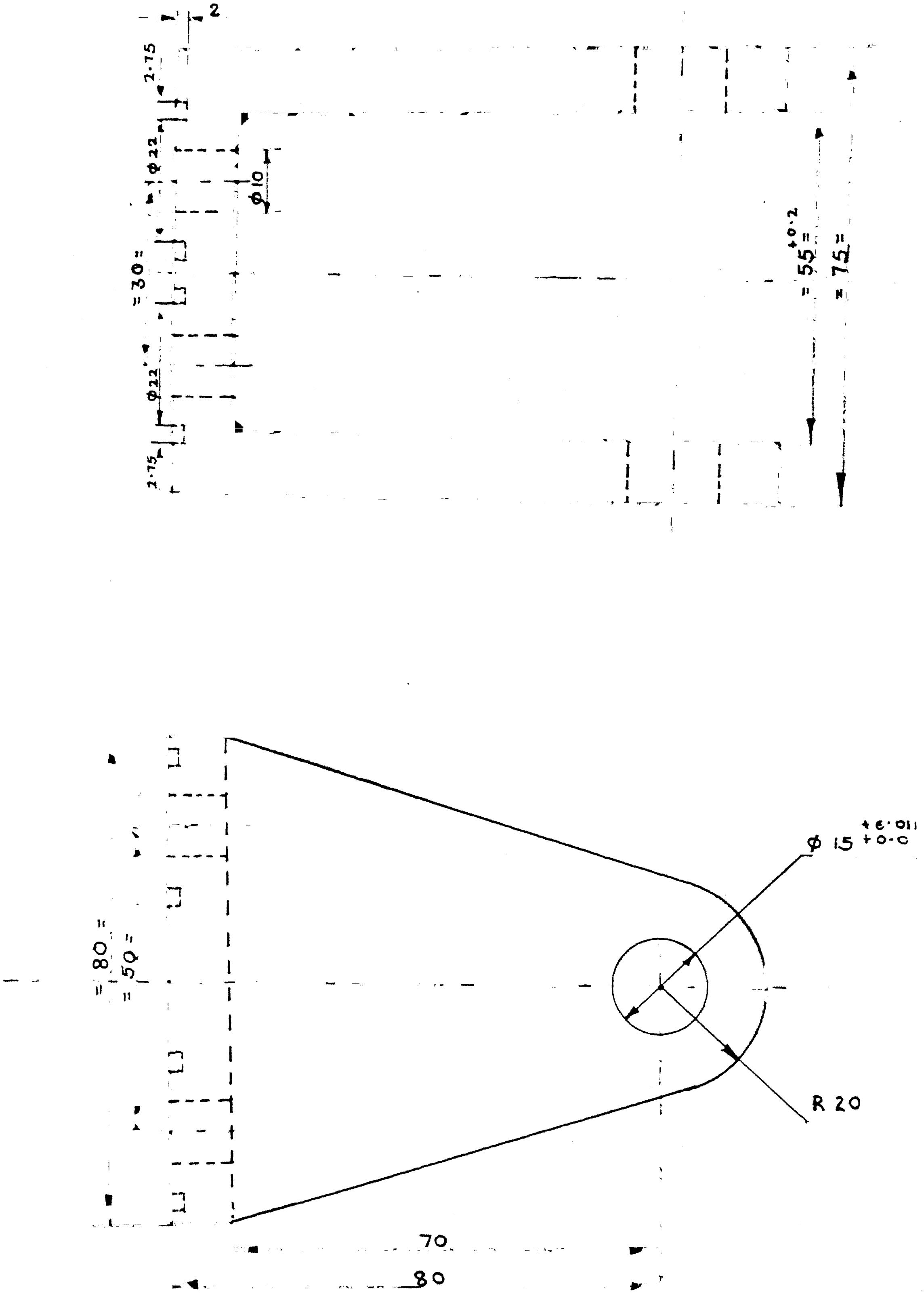


FIG. 18 FIXED BRACKET P.No. 1

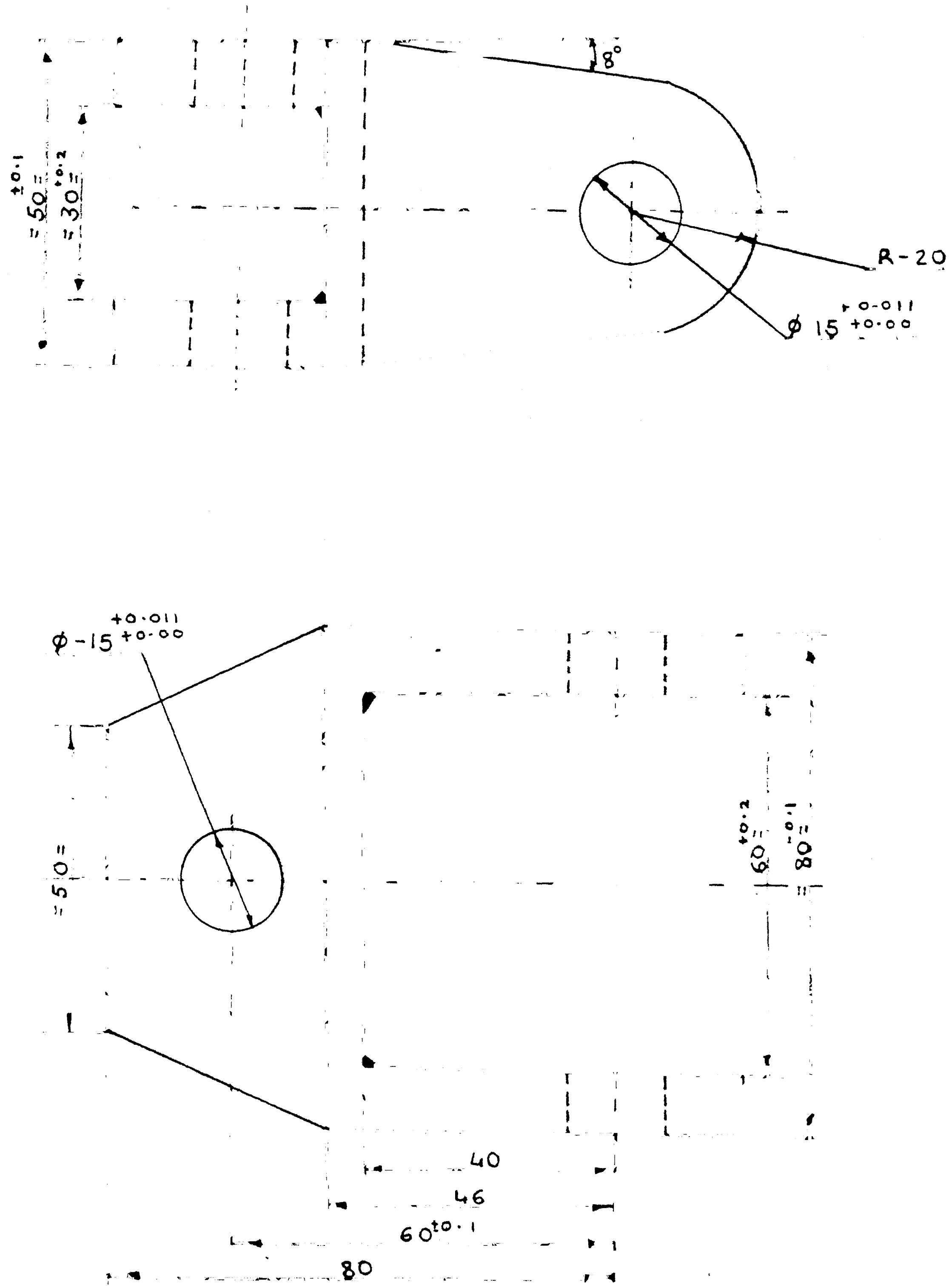


FIG. 19 CONNECTOR P. No.4

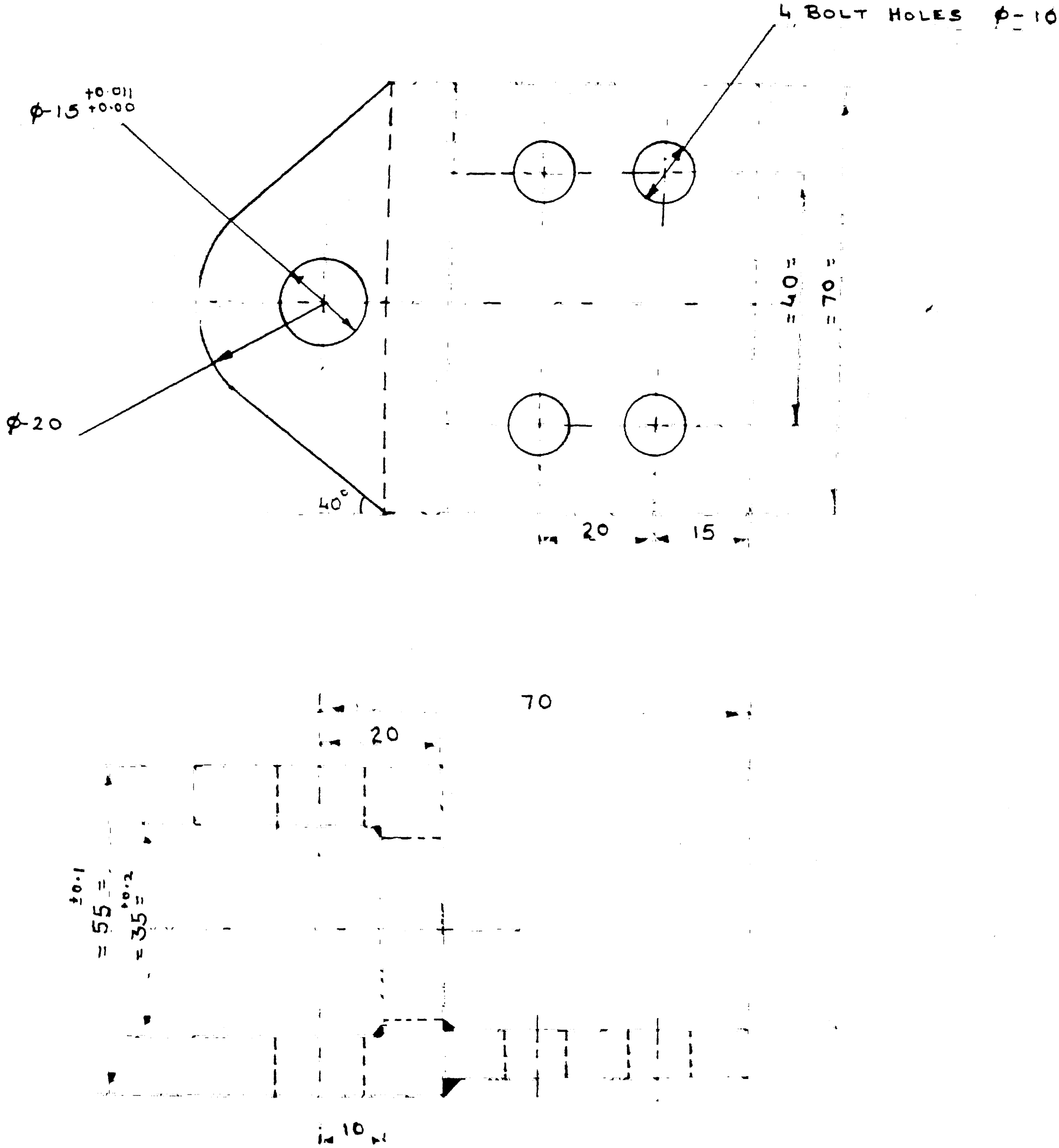


FIG. 20 BRACKET FOR CABLE P.No. 7

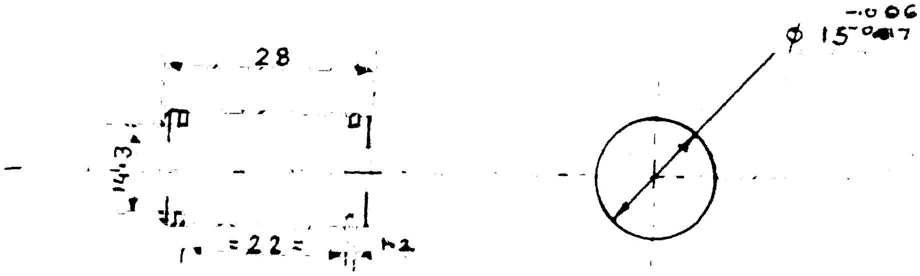


FIG. 21 PIN P. No. 2 & 5

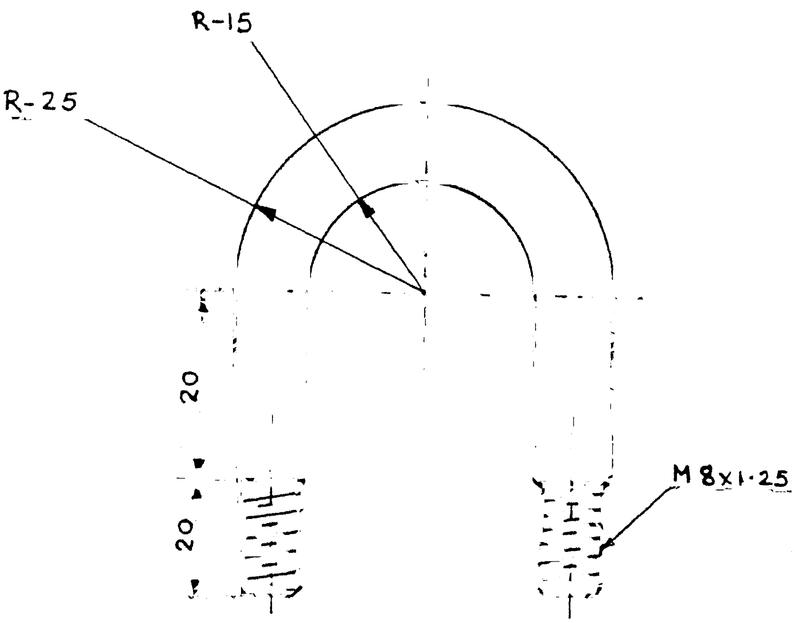


FIG. 22 U-CLIP P. No. 8

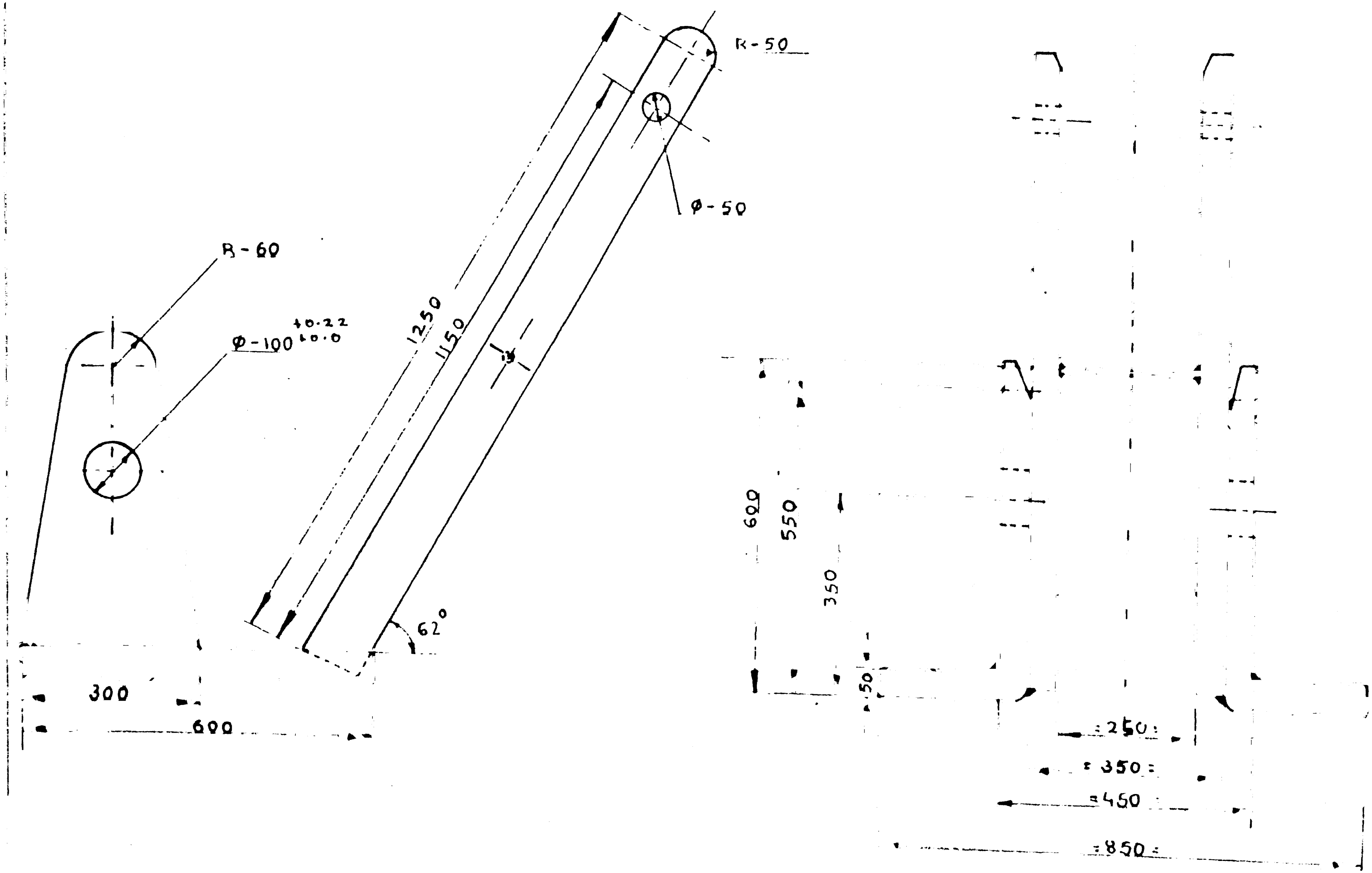


FIG. 23 WINCH BASE

P. No. 1

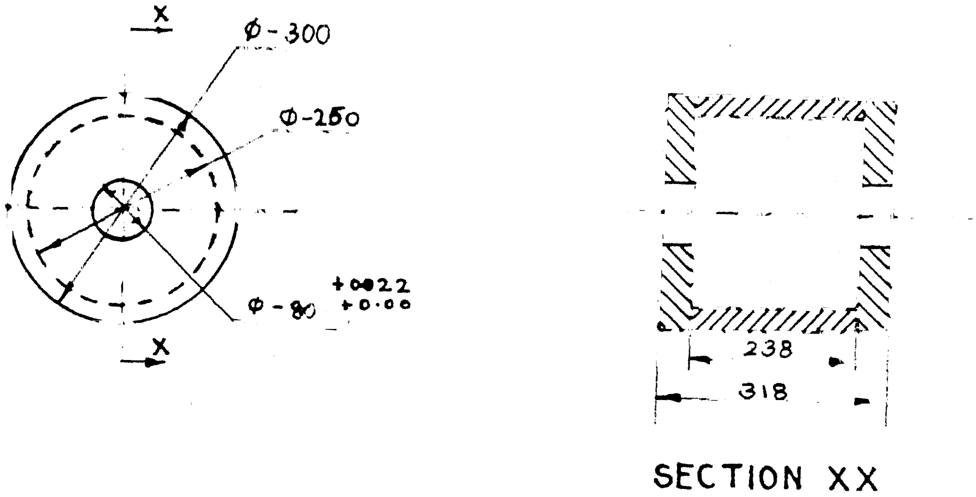
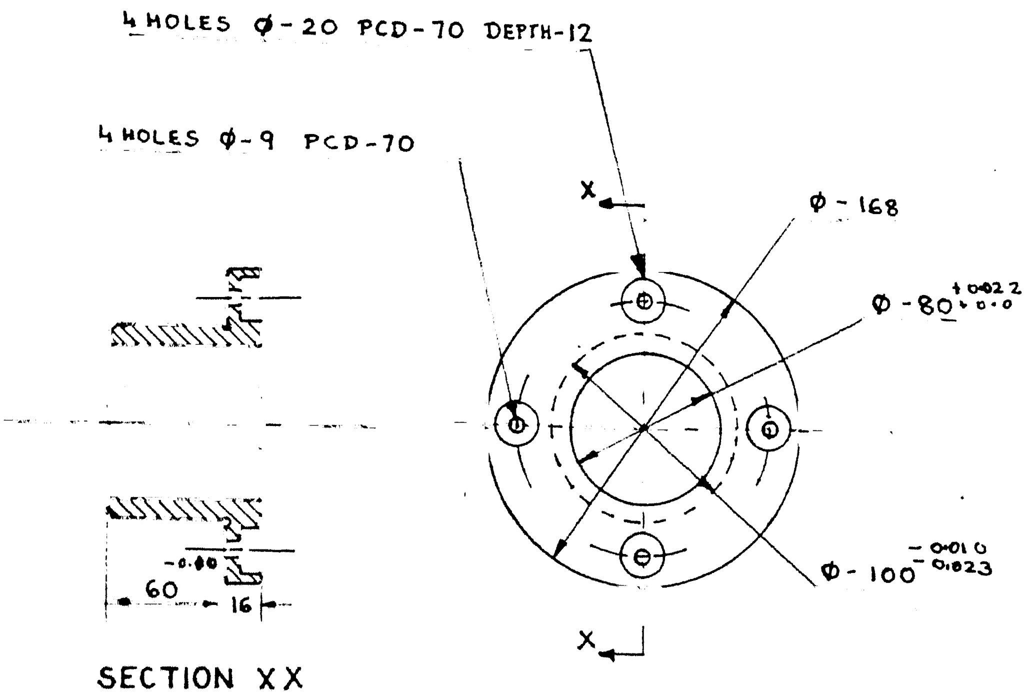


FIG. 24 PULLEY P. No. 2

FIG. 25 BUSH P. No. 4



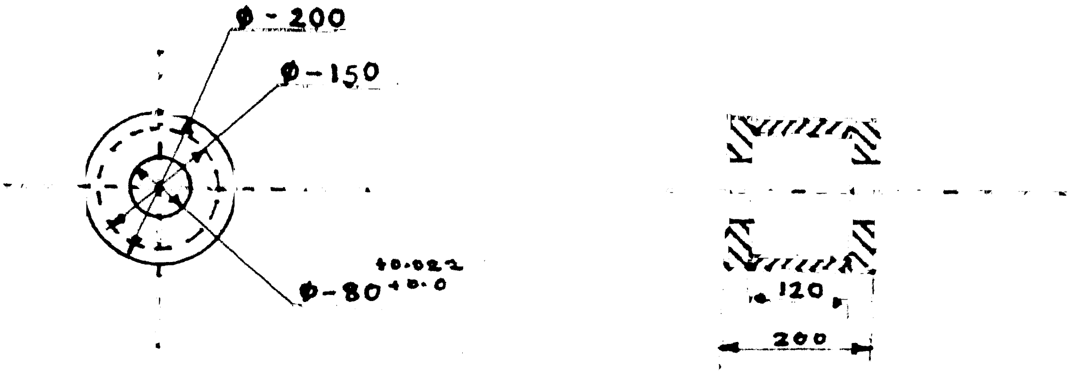


FIG. 26 DRUM P. No. 3

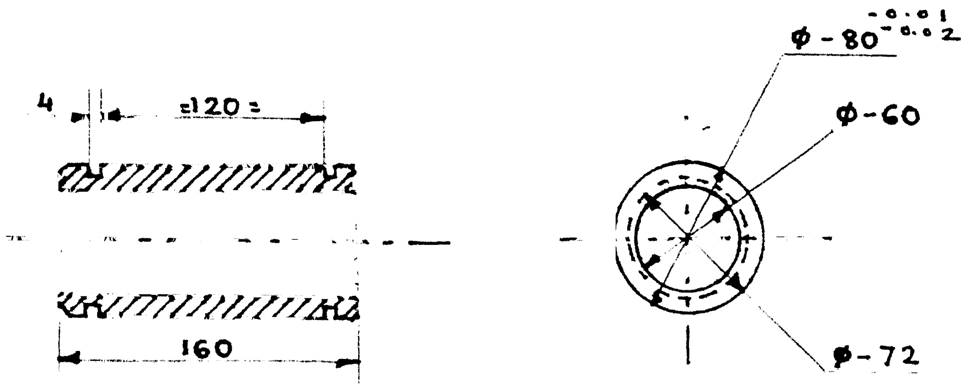


FIG. 27 SHAFT P. No. 5

APPENDIX - B

SPECIFICATIONS OF VEHICLE COMPONENTS

Table 1. PROPELLER SPECIFICATIONS

Horizontal Propeller

a] Propeller Diameter : 0.26 m

b] Pitch/Diameter ratio : 0.67

c] Optimum Efficiency : 0.45

Vertical Propeller :

a] Propeller Diameter : 0.4 m

b] Pitch/Diameter ratio : 0.65

c] Optimum Efficiency : 0.44

Table 2. D.C. SERVO MOTOR SPECIFICATIONS

a] Motor Make : Yaskawa Hi- Cup Motors

b] Motor Model : UGHMED - 03GG1

c] Overall Dimensions : 200 ϕ * 250 1

d] Gross Weight : 120 Kg

e] Rated Power : 250 W

f] Rated Torque : 2.4 N.m

g] Rated Speed : 1000 rpm

h] Armature Voltage : 55 V

i] Armature Current : 7.8 A

j] Torque/Inertia : 1159 rad/sec^2

i] Maximum Torque : 12 N.m

j] Maximum Speed : 2500 rpm

k] Maximum Current : 38 A

Table 3 . CAMERA SPECIFICATIONS

a]	Camera Make	:	Pulnix Miniature CCD Camera
b]	Overall Dimensions	:	60 ϕ * 200 l
c]	Weight	:	7 N
d]	Resolution	:	280 * 350 lines
e]	Lens	:	8.5 mm, f1.6 , auto iris
f]	Minimum Illumination	:	3 Lux
g]	Operating Voltage	:	12 V D.C

Table 4. PAN AND TILT MECHANISM SPECIFICATIONS

a]	Overall Dimensions	:	180 * 260 * 300 mm
b]	Pan Motion	:	360°
c]	Tilt Motion	:	270°
d]	Total Weight	:	100 N

Table 5. STEPPER MOTOR SPECIFICATION

a]	Type	:	STM 602
b]	Overall Dimensions	:	60 ϕ * 100 l
c]	Torque Rating	:	0.4 N.m
d]	Operating Voltage	:	6 V

Table 6. LIGHT SPECIFICATIONS

a]	Light Type	: Tungsten Halogen Incandescent
b]	Overall Length	: 111 mm
c]	Power	: 100 W
d]	Initial Intensity	: 1340 Lumen
e]	Operating Voltage	: 120 V
f]	Average Life	: 200 hr

APPENDIX - C

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